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Martin Rössler, Wolfgang Laube, Philipp Weihs

Final report
on behalf of ASFINAG, Bundesministerium für Verkehr,
Innovation und Technologie, Wiener Umweltanwaltschaft

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Avoiding bird collisions with glass surfaces

Experimental investigations of the efficacy of markings on glass panes under natural light conditions in Flight Tunnel II

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Hohenau a. d. March, March 2007

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CONTENTS

1 INTRODUCTION

Collisions with window panes are among the most significant anthropogenic mortality factors of birds (KLEM 1990). Collisions occur in settlement areas, e.g. with glass fronts, as well as in open landscape; for example along road axes (noise barriers) etc. Birds are affected indiscriminately, independent of species, age, or sex. Markings on glass panes are regarded as a way to avoid bird collisions. In order to assess and increase the efficacy of such markings, reliable studies at the interface of planning and bird protection are needed, comprising both the aesthetic demands of affected persons and the requirements of bird protection.

Figure 1: A new experimental tunnel (Flight Tunnel II) in Hohenau-Ringelsdorf serves to continue the research of the years 2004 and 2005 with enhanced facilities, in order to enable better prognoses of the efficiency of markings to reduce bird strikes against glass planes. Flight tunnel II, here not in use, mirrors covered.

The ineffectiveness of adhesive silhouettes of birds of prey has been tested – and confirmed – in several studies (e.g. KLEM 1990, TRYBUS 2003). The effectiveness of UV-reflecting markings, which are invisible to humans but can be perceived by birds, as proposed by BUER & REGNER (2002), was investigated by LEY (2004) and was confirmed in one case under artificial light conditions. At the Biological Station Hohenau-Ringelsdorf (Lower Austria), research is done on markings visible to the human eye, which are considerably more effective (see Ch. 4.4).

Experimental investigations have been conducted at the Biological Station Hohenau-Ringelsdorf since 2004, linked to the work of the bird ringing station (Ch. 1.2.1). The experiments at Hohenau are accompanied by a large number of control and repeat trials (Ch. 2.10), which show a very high repeatability of results and enable a reliable differentiation between several markings where this is justified statistically.

In the years 2004 and 2005, the research focused mainly on shape, density, and size of the markings and the amount of area covered by them. To tackle the more complex problem of the effects of light and contrast, a new experimental set-up was necessary. This required the design and construction of a turnable flight tunnel, with lateral mirrors reflecting sunlight onto the experimental panes (Fig. 1).

The project was commissioned by the ASFINAG (the state corporation for financing roads and highways) and the BMVIT (Federal Ministry of Transport, Innovation and Technology). Funding for the experiments from 2004 to 2006 came from the Wiener Umweltanwaltschaft (WUA, Vienna Ombuds-Office for Environmental Protection), complemented by contracts awarded by the City of Vienna (MA 29) and the "Para-Chemie" company.

The exploration of new and the optimisation of effective markings (e.g. minimal percentage cover, smallest object size etc.) will stay an important objective of our experiments also in the future. The fact that in our experiments markings consisting of 2mm wide lines covering just 6.7% of the total area were shown to be effective (Acrylic horizontal), shows that there may be ample scope for reducing the potentially inconvenient conspicuousness of the markings (RÖSSLER 2005).

1.1 The basic task

The main question is: Are some markings perceived by birds and is the danger of collisions by birds flying towards the glass front significantly reduced as a result?

Markings are sought that

- optimally prevent collisions
- cover only a minimal area
- are cheap to produce and long-lasting
- are widely accepted by the public

This question is to be investigated experimentally under near-natural light conditions.

1.2. Review

1.2.1 Flight tunnel I (2004 – 2005)

The Hohenau concept of 2004 is based on synergies with the bird ringing activities of the ringing station Hohenau-Ringelsdorf and is designed to give birds in an experimental tunnel a choice of flying towards either a marked or an unmarked pane. The first experimental tunnel "Flight Tunnel I", with a length of 7.50m, was located outdoors next to the ringing station. It is described in detail in RÖSSLER & ZUNA-KRATKY (2004).

Basic concept:

- Tendency of birds to fly from the dark toward the light (attractor light)
- High efficiency by a combination of mist net trapping (360m² of mist nets) and trials with a 1m² glass pane/ test-area (exchangeable experimental panes)
- A limited number of variables; large sample sizes; statistical differences between markings can be shown
- No collisions; no mortalities; birds are captured by mist nets prior to colliding with the pane

- Complete documentation of all trials
- Good timing of the investigation period: July/August: after breeding, highest occurrence of birds
- 1000 birds per year
- 10 alternative test set-ups per year (n > 90)

In Flight Tunnel I, the light conditions differed from conditions outdoors. Initially, this was of lesser importance, as the primary aim was to investigate basic patterns of visual perception and related behaviour.

1.2.2 Results from experiments 2004 – 2005

13 markings were tested during 1,996 trials in flight tunnel I (RÖSSLER & ZUNA-KRATKY 2004, RÖSSLER 2005).

- One marking turned out to be ineffective.
- Twelve markings, covering between 6.7% and 25% of total pane area proved to be effective.
- Percentage cover and effectiveness were not necessarily correlated.
- Five markings, covering <20% of total area, were recognized and avoided in over 90% of trials.
- Three markings covering <20% of total area were recognized and avoided in over 95% of trials.
- Horizontal lines spaced 10cm apart were significantly less effective than vertical lines spaced 10cm apart.
- A horizontal marking consisting of 2mm-wide black lines (spaced 2.8cm apart, covering 6.7% of total pane area) was effective.
- A screenprint marking covering 25% of total pane area was less effective than markings of adhesive tape covering between 16 and 27% of total pane area.

1.2.3 Methodological findings

- The results from one marking that was tested in both years (2004, 2005) show that the results are repeatable and that a sample size of approximately 100 birds is sufficient.
- Video documentation is essential (Ch. 2.11).
- Daily activity of birds: 50% of the birds are available for experiments between 5:00 and 9:00am. Since there is a close temporal relationship between bird activity, capture success, and experiments, the experiments automatically take place during the most important times of day and thus under representative light conditions.
- The experiments are influenced by the position of the sun; therefore the direct effect of the sunlight must be eliminated, or the sunlight has to come from always the same direction.

1.3 Further development of research questions and methods

1.3.1 Evaluation of methods used until 2005

In 2004 and 2005, we focused our attention solely on the type (size, arrangement, percentage cover) of different markings. For the first time, the experimental results showed statistical differences between very similar markings. However, starting in summer 2005, new ways to improve the experimental methods were considered. Different elements of the methods were evaluated, whereby the following principles were regarded as essential:

- choice trial
- flight tunnel
- free-living wild birds; single trial
- random order of markings
- random positioning of the marked glass pane in the left or right side at the end of the tunnel
- Change of the experimental panes after three trials
- Sample size n = +/-90
- Documentation on videotape

1.3.2 New variables – light and contrast

One component that had been neglected in the previous experimental set-up was the presumably unnaturally high contrast with the background, due to the darkness in the tunnel at the bird's /marking's side and the daytime light behind the glass panes. However, this differed from natural conditions. It was therefore necessary to refine the methods to avoid this problem. In order to assess the relevant variables, the physical properties of the light and current knowledge about visual perception of birds and their behaviour were included.

The higher the contrast between a dangerous glass pane and the natural biotope, and the better warning signals are displayed, the lower the risk of bird collisions should be. Through evolution, numerous interrelations in visual ecology visual have developed in nature, for instance between predator and prey, between potential mates, between flowers and pollinators, and between fruits and their dispersers (Ch. 4.3.2). Through selection, visual systems have evolved which in many cases are based on contrasting effects.

The following variables are crucial in influencing the contrasting effects of glass surfaces:

- Optical properties of the markings
- Optical properties of the glass panes
- Light conditions in front of and behind the panes

The new flight tunnel should make it possible to include the important physical-optical factors and their variability. This required:

- Illuminating the experimental panes on the side facing the bird
- Assessing the optical properties of the markings and the glass panes
- Recording and modelling of light conditions during the experiments

1.3.2 New methods – how much nature, how much lab?

The question was to what extent the experiment should be transferred from its “semi-natural experimental design” to an increasingly artificial lab situation; or how some specific requirements could be fulfilled while maintaining the “semi-natural approach”.

In particular, the questions whether to use

- artificial or natural light
- an artificial or a natural background

were very difficult to decide. When deciding between artificial illumination and natural light, different criteria were considered (Table 1). Furthermore, the specific conditions at the experimental site had to be taken into account, for example that the ringing station is not connected to the electricity grid. The choice of background was facilitated by the fact that the vegetation was very homogenous, providing very favourable conditions for the experiments.

Table 1: Criteria for choosing the light source; advantages and disadvantages of artificial and natural illumination and conceptual consequences for Flight Tunnel II.

Criterion	**Artificial light**	**Daylight**
No disrupting lights in the flight tunnel	Possible reflections by spot lights are problematic; lamps need to be located laterally of the panes	Possible if panes are installed in front of the tunnel and sunlight is reflected into the tunnel
Pulsation-free illumination to avoid unnatural stroboscopic effects on the markings	Problematic; the electric arcs of fluorescent lamps may cause a 50 Hz or high frequency flickering; no such problems with incandescent lamps and LED.	Yes
Parallel incidence of light	Only possible with elaborate optic devices (parabol mirrors or lens systems)	Yes
Symmetric incidence of light	Yes	Yes, if tunnel turnable
Even illumination of panes	Possible, but complicated	Possible with direct sunlight; with diffuse light dependent on the horizon
Incidence of light without creating a harsh shadow	Yes	Yes, if direct incidence of sunlight onto the panes can be ruled out for all positions of the sun (sun shields)
Spectral composition of the light identical to that of natural light from 350nm upward	?	Yes, if mirrors reflect UV-A light (mirror with a chrome surface?, permeability to UV-A of the glass used?)
Background of the pane	Must be artificial, otherwise a confounding variable; illumination corresponding to the front of the pane; attractor possibly weak; requires a complete enclosure	Either artificial (attractor possibly weak, at low sun shadows may be generated by the tunnel or natural vegetation (attractor strong, continuity to 2004-2005, constant angle of incidence of light due to turnability of the tunnel)

Criterion	Artificial light	Daylight
Wind stability, no vibrations	Yes	Yes, if solid construction (anchorage of the turnable tunnel and the high mirrors)
Recording of light parameters (depends on the level of precision required, low tolerance when using artificial simulations, higher tolerance under “semi-natural” experimental conditions)	Control of spectral composition of the light, very complex	Continuous measurement of light intensity (photovoltaic sensor), recorded by a data logger; values can be obtained for each test trial; level of illumination can be calculated using a model
Operability	Complex; supply of power set, pre-heating of lamps, maintenance of electric equipment, control measurements of light spectrum emitted	Simple; turning the tunnel according to the position of the sun, covering the mirrors when not in use to avoid bird collisions, regular readout of the data logger (see above)
Energy supply	Power set for illumination	Only small-sized appliances with rechargeable batteries
Costs	High, plus continuous costs	High but non-recurring costs

Any particular light condition is the result of a large number of interacting variables (direct sunlight, diffuse radiation from the sky, radiation reflected from the ground, vegetation and objects in the environment, Ch. 4.3.1.) and is dependent on the exposition of the pane, the position of the sun, weather and the ambient environment. Thus, there is an obvious temptation to simulate a particular light condition using electric illumination of a known constant light intensity and spectral composition. However, even when making use of all the technology available today, some problems occur when using electric light (Table 1).

- Light rays originating from relatively nearby light sources do not hit the panes in a parallel fashion and as a result cause gradients of light intensity (Lambert’s cosine law)[1].
- Point sources reflecting light in the direction of movement of the bird. To avoid this, the light has to come from the side. Based on the geometry of the tunnel and possible flight paths of the bird, the angle of incidence is approximately 35° for points close to the edge of the panes and <10° for points that are further away from the edges, i.e. in the centre of the panes.
- Neither incandescent lamps nor fluorescent lamps, nor LED can simulate light conditions that comply with general expectations of daylight conditions. Moreover, it is difficult to achieve high, and in particular continuous, power supply in the field (power set) and the amount of light emitted varies with the operating temperature of the lamps (which would thus need to run continuously). In addition, the lamps deteriorate with time (especially LED).
- When the illumination in front of the panes is defined, the background of the panes must also receive a clearly defined amount of illumination in order to generate different classes of contrast. This would

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[1] Lambert’s cosine law: the relationship between light intensity and incidence angle. Light intensity declines with increasing cosine of the angle of incidence. The shallower the angle of incidence, the lower are density of radiation and light intensity; cf. 4.3.1.1.

require a complete enclosure of the apparatus, removing daylight and vegetation, and would pose new problems regarding the transferability of the results to natural conditions.

► Overall, clearly defined light conditions that correspond to natural conditions cannot be achieved to the desirable extent using artificial illumination. Therefore, after some experiments, the “artificial illumination” approach was discarded. For similar reasons, i.e. the fact that advantages only seemed to predominate, we decided against using an artificial background coloured uniformly in grey.

Thus, we deliberately put up with the variability of the light and the background and subsumed the chance aspect of natural events as “natural conditions”. It is important to be aware of this when analysing the results. However, many of the influencing variables can be measured and documented, and they can be reconstructed in models (Ch. 2.7) for the times at which the experiments took place.

2 METHODS

2.1 The tunnel

2.1.1 Planning and preliminary tests

First approaches and outlines of the new experimental design were developed in the course of the experiments in 2005. The concepts were substantiated through a cooperation between the Biological Station Hohenau-Ringelsdorf and the Institute of Meteorology of the University of Applied Sciences Vienna, starting in December 2005. Thus, practical experience with the specific experimental procedure and concrete ideas about suitable experimental conditions were combined with expertise about radiation, light composition, and measurement and interpretation of physical parameters.

Prior to construction of the tunnel, preliminary trials were performed. Experiments modelling geometric relationships when sunlight is reflected into the tunnel: With simple means, a model of the tunnel was built to scale, and the path of the sun was simulated using a strong light source in a lecturing theatre (Fig.2). Thus, light yield was assessed for various arrangements and sizes of the mirrors. When the decisive factors were known, calculations of the required position, size and angle of the mirrors were carried out. Figure 3 shows the construction in the production hall.

2.1.1.1 Measurements and geometry of the experimental tunnel

The basic measurements of the new experimental tunnel do not differ from those of tunnel I; however, instead of an oblong outline, a trapezoid outline was chosen (see below). The measurements are: length 7.50m, height 1.30m, width at the proximal end 1.25m, at the distal end 0.40m. The experimental panes (0.50 x 1.00m) are mounted 30 cm in front of the tunnel in holding fixtures which allow easy exchange of the panes. A holding fixture consists of a chip tray which is dimensioned such that from inside the tunnel, the sky and the vegetation can be viewed only through the experimental panes. A mist net 0.40m from the panes prevents the test birds from colliding with the glass. Depending on the bird's flight path, the mirrors enter the bird's field of view at a maximum of 20cm away from the mist net (at a speed of 5ms^{-1}; 0.04s before colliding with the net).

The tunnel is mounted on a turntable at its centre of gravity so that it is turnable and can be adjusted manually, with little effort, to the changing (compass) angle of incidence of the sun. Due to the tunnel's tapering shape (2.5°), there is a tolerance of 5°, when tracking the sun's position. During this time, the tunnel does not need to be moved. Up to a solar height of 50°, direct sunlight (provided the sun is shining) hits each point on the experimental pane at any time of the day. A sunshield above the tunnel chamber prevents the panes from being hit by direct sunlight and thus harsh shadows on the markings are avoided.

The choice of distance between the tunnel and the glass panes must take into account the following considerations:

- The greater the distance between the panes and the tunnel, the greater can the solar angle of incidence to the experimental panes be, but the wider and higher must the mirrors be.
- The closer the panes are to the tunnel, the more slanted must the incidence of direct sunlight to the panes be, the lower is light intensity due to Lambert's cosine law, and the lower is the incidence of diffuse radiation.
- The distance between the tunnel and the experimental panes determines the amount and the distribution of diffuse light reflected from the sky and the vegetation. Under clouded conditions, when there is a lack

of incident solar radiation, a reduction of the distance between the panes and the tunnel leads to a decrease in the amount of diffuse radiation and illumination of the panes.

- Since the net distends by up to 30cm, the panes must be located at least 30cm away from the net; otherwise the set-up would be life-threatening for the bird.
- A distance of more than 40cm is impractical for the size of the experimental panes used (50 x 100cm), as the panes would then no longer dominate the bird's field of view.

Figure 2: In the lab, the suitability of mirrors was tested in simplified experiments, and a favourable optical path was determined.

Figure 3: From model to realisation: here the mirrors (0.65m x 2.50m) with the nearly-completed tunnel in the production hall.

The dimensions of the mirrors (0.65m x 2.50m) are calculated based on the optical path of the light, the distance to the panes, the width of the panes, and the critical altitude of the sun (50°). The angle of the mirrors to the plane of the sunrays is 32°; accordingly the angle of incidence to the panes is 26°. As explained by Lambert's cosine law (Ch 4.3.1), illumination thus reaches about 35% of the illumination level that would occur if the sunlight hit the panes directly. The direct, reflected sunlight illuminates all points of the (marked) panes equally.

While the mirrors reflect direct light equally to each point on the experimental panes, the amount of diffuse light depends on how much of the sky is visible at different points on the pane (Fig. 4). In conditions with low solar radiation, light intensity increases with increasing distance between the tunnel and the experimental panes.

2.1.1.2 Temporal limitations due to the altitude of the sun and the height of the mirrors:

When planning the tunnel, the maximum solar height for experiments was fixed at 50° so that the height of the mirrors could be limited to 2.50m. However, this causes some temporal restraints. Table 2 shows the critical times of day and the peak height of the sun in Hohenau at different times of the year. In the beginning of July, use of the tunnel for experiments was not possible during five hours per day, in the beginning of August during four hours. However, we know from experience that 50% of the birds are captured prior to 9am and only very few are captured at midday, therefore this limitation was deemed acceptable, as not many trials were lost.

Table 2: Times of day at which solar height exceeded or fell below 50°; data for the ringing station Hohenau-Ringelsdorf in 2006

Date	Time at which a solar height of 50° is reached		Peak height (°)
	ascending	descending	
1st July	10:20	15:35	64.5
8th July	10:25	15:30	63.9
15th July	10:30	15:25	62.9
22nd July	10:35	15:20	61.7
29th July	10:45	15:10	60.1
5th Aug.	11:00	14:55	58.4
12th Aug.	11:10	14:40	56.3
19th Aug.	11:30	14:20	54.1
26th Aug.	12:00	13:50	51.8
31st Aug.	50° not exceeded		50.0

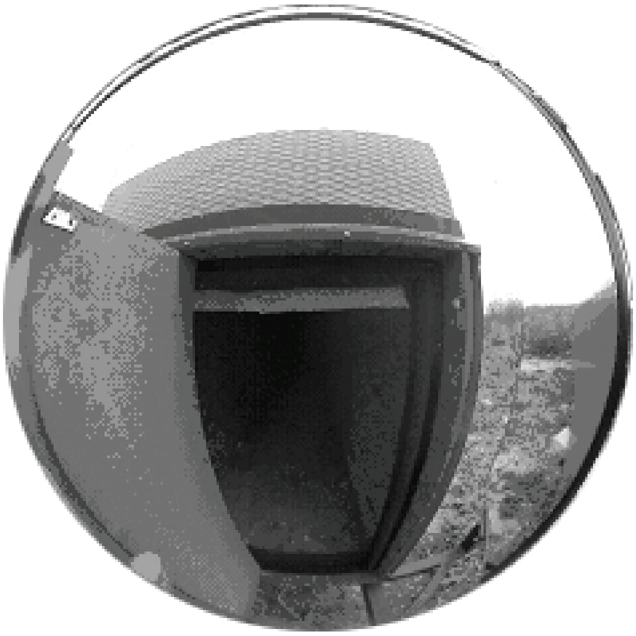

Figure 4: Fisheye picture taken from the level of the glass panes. On the left: partition between the experimental panes. On the right: mirror, discernible by the slight discontinuity in structure.

2.1.1.3 Suitable mirrors (UV-reflectance)

Since it was necessary to transmit UV-A radiation (350-400nm) from the sunlight to the markings, it was considered whether glazed mirrors could fulfil these requirements (possible UV-absorption), or whether it was necessary to use surface mirrors. At first, no producer of surface mirrors could be found; therefore we commissioned some galvanisers to chrome-plate brass sheets and tested the reflection of different quality grades of polishing, comparing these with a conventional high-quality glass mirror. At the last minute, we received a further sample of an industrially made special mirror, the composition of which remained unknown to us.

Fig. 5 shows the results of the double monochromator measurements. The curves indicate spectral reflectance of the mirror, measured in 10nm steps as % of directly incident sunlight (for information about the measuring method see Ch. 2.2.1).

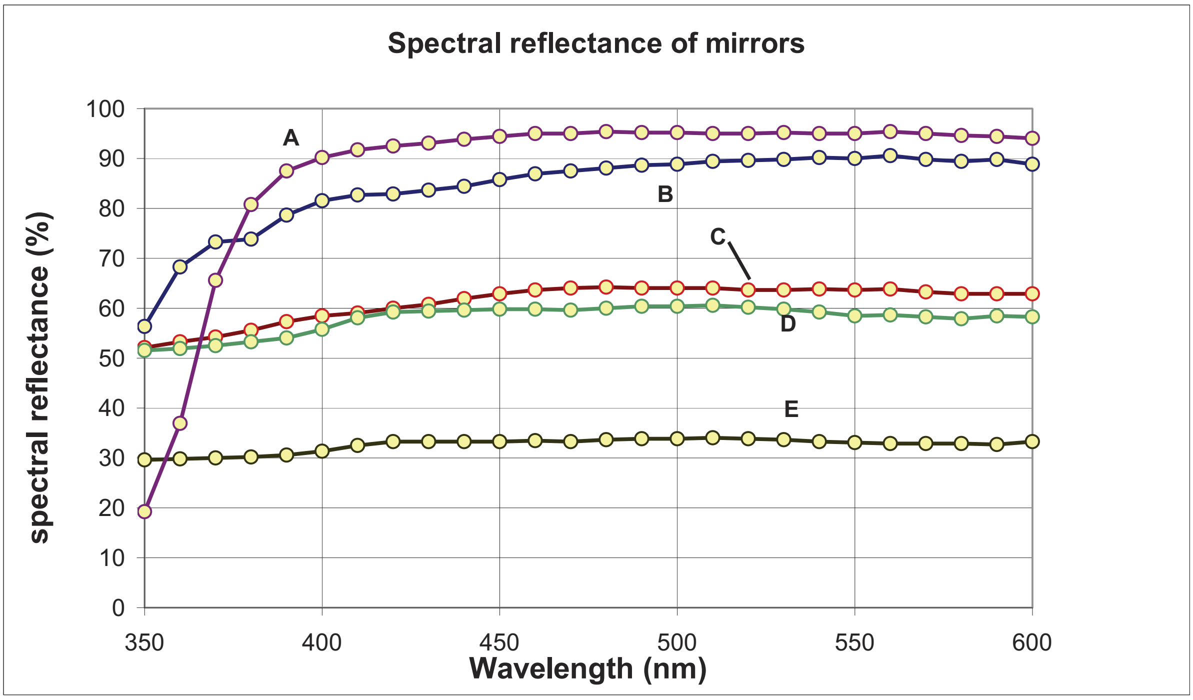

Figure 5: Reflectance of an industrially made surface mirror (A), an industrially made silver mirror with 3mm float glass (B) and three chrome-plated metal sheets of varying qualities of polishing (C, D, E). The surface mirror (A) reflects visible light better than the conventional mirror (B), but is inferior to the conventional mirror in the UV-A range. Reflectance of the chrome-plated sheets (C-E) was very dissatisfactory overall.

In two cases (A, E), UV-reflectance at 350nm was less than 50%. All chrome-plated sheets yielded very similar results (reflectance 52%) despite considerable differences in the degree of polishing; the silver mirror achieved 56% despite 3mm of float glass. Total reflectance is considerably lower for the chrome-plated surfaces (C-E) than for A and B. Total reflectance of the special mirror (A), more than 90% in the visible spectrum, is much better than reflectance of the conventional mirror (B). Nonetheless, we decided against mirror A due to its low UV-reflectance, as well as the financial aspect. We made our choice for the conventional glass silver mirror (B).

2.1.2 Construction

The tunnel was built by Fa. Schweinberger, Landmaschinen- und KFZ-Werkstätte, 2273 Niederabsdorf.

Into a 5t-concrete base a framework of 1m-long threaded rods, serving for later fitting of the turntable, was anchored. After construction the tunnel was transported by flat-bed truck to the ringing station. Mounted on two wheels, the tunnel was hauled to the base with the turntable. Using a tractor's hydraulic system, it was positioned precisely and welded onto the turntable.

Figure 6: The tunnel was taken to the ringing station by a flat bed truck…

Figure 7: … and welded onto the turntable, which had been put into an exactly horizontal position.

The tunnel was completed in time and budget, without any planning or construction errors, or other faults which would have required subsequent corrections.

Table 3: Production steps in the construction of flight tunnel II

Calendar week	Production steps
21st week	Cutting to size of the panels, assembly of the timber construction, and construction of the supporting structure from hollow steel tubes.
22nd week	Holding fixtures for the mirrors and the mounting plate for the experimental panes, selection of mirrors.
23rd week	Delivery of mirrors, paintwork, preparation of the future site of use.
24th week	Construction of the base and mounting of the turntable at the construction site, calibration of pyranometers and dataloggers.
25th week	Construction of the tunnel: delivery of the tunnel by flat-bed truck, transport of the tunnel to the site of use set-up of the turntable and adjustment of the tunnel into a horizontal position, wind bracing, light measurements, initial flight trials
26th week	Sheet metal covering, precision work (birds' safety, starting box), flight trials, standard measurements of light
27th week	Normal use of the apparatus

2.2 Measurements

2.2.1 Measurements in the lab

Optical measurements were performed in the light laboratory of the Institute of Meteorology of the University of Applied Sciences Vienna, in a completely black room. A double monochromator (Jobin Yvon HRD1, 650mm, with Photomultiplier Tube 8250 U), measuring radiation at 10nm-intervals, and a halogen light (H3 with a UV-permeable jacket), with a spectral range of 300nm to 600nm, were used in the assays.

2.2.1.1 Transmittance of the panes

For measurements of transmittance, the glass panes were mounted at a distance of 60cm from the monochromator's entrance slit, perpendicular to the optical axis of the entrance slit. The light source was located in the optical axis behind the experimental panes. Reference measurements were taken with the same configuration but without the glass panes.

2.2.1.2 Reflectance of the markings

For measurements of reflectance, the glass panes were mounted vertically at a distance of 15cm from the monochromator's entrance slit. The light source was located underneath the test piece. A surface mirror reflected the light onto the pane, at a small angle to the optical axis. As a reference colour (white), a surface coated in magnesium oxide was chosen. The coating was applied onto a carrier object immediately prior to the assays. Results from the glass panes were compared with the reflectance data from the magnesium oxide reference.

2.2.2 Measurement of light conditions during the experiments

For measurements of radiation, two silicon photovoltaic sensors (Environmental Measurement Systems EMS 11) were attached to the tunnel. The photovoltaic sensors (pyranometers) measure the entire incident radiant energy between 400 and 1,100nm. One sensor (pyranometer 1) is located on top of the tunnel, approximately 2m above the ground. Positioned in a horizontal measuring plane, it measures celestial radiation and direct solar radiation (Fig. 8). The second sensor (pyranometer 2) is mounted in a vertical measuring plane at the back of the holding fixture, approximately 2.5m above ground (Fig. 9). This sensor measures radiation, composed of diffuse celestial radiation and reflectance from the vegetation, behind the panes. Measuring intervals are 10 seconds; the data are recorded by a datalogger (EMS Mini Cube) as averages for each minute. During the period of investigation, the data were read out on a weekly basis and saved on an external PC.

Figure 8: Pyranometer 1 for measuring global radiation

Figure 9: Pyranometer 2 for measuring radiation behind the experimental panes

2.3 Planned investigations

For 2006, a first series of experiments with eight types of markings was planned, which should be finished by the end of July. A second series of experiments with four to six markings, chosen based on the results of the first series, was planned for August. However, as capture success for July was far below the norm (just half of the mean of many years, Ch. 2.9) completion of the first series lasted far into August and the second series had to be cancelled.

2.3.1 Marked panes

The choice of markings (Ch. 2.4.1) was based on the following aims:

- To re-test, under the conditions of flight tunnel II, some markings that were particularly important or representative and had already been tested in 2004 or 2005
- Based on results from previously tested markings, to reduce the area covered (how little is too little?)
- To investigate black, white and mixed types on the basis of results from previously tested markings

2.3.2 Acrylic with UV-absorbers

In 2005, the acrylic pane „PLEXIGLAS SOUNDSTOP®“ (marking „Acrylic horizontal”) was more effective than expected. Since acrylic glass has different optical properties from float glass (Ch. 2.5), it was necessary to test whether this result could be explained by optical differences to the control pane. While acrylic glass normally has a higher UV-transmittance than float glass, this was not the case for the panes used in the experiment. As shown in Fig. 12, the pane only starts transmitting considerable amounts of light above wavelengths of 390nm. This can be attributed to admixed UV-absorbers, which are added to increase durability. In order to test whether the high effectiveness of PLEXIGLAS SOUNDSTOP® could be due to the optical properties of the material, the “effectiveness” of an identical, but unmarked, pane was tested.

2.3.3 The glass vs air experiment

Up to now, there was no experimentally shown basis for the claim that birds cannot detect glass. In flight tunnel I, it was not possible to test this, as the experimental panes were positioned directly at the front end of the tunnel, closing it off. If one pane had been missing, this would have caused discontinuities in acoustic properties and air currents that would have interfered with the experiment. In flight tunnel II, there is a gap of 30 cm between the tunnel and the panes; thus this experiment was now possible. The tests were conducted in the same way as usual; instead of randomly exchanging the marked panes or switching sides, only one unmarked pane was placed into the holding fixture, in a random order at either the right or the left side.

2.4 Markings

2.4.1 Explanation for the choice of markings

In order to distinguish between the factors „shape“ and „light“, four tests conducted in 2004 or 2005 were repeated under the new experimental conditions (Ch. 2.4.1.1). To further develop markings that fulfilled our objectives, four new markings were tested (Ch.1.1). The main aim was to investigate how much the percentage cover, the width of the lines etc. could be reduced (Ch. 2.4.1.2) and which role achromatic contrasts – in particular black and white markings – played (Ch. 2.4.1.3).

2.4.1.1 Replication of experiments from 2004/2005 in flight tunnel II

Acrylic horizontal: The 2005 results showing a very high efficacy of acrylic panes marked with black polyamide stripes were regarded with reservation, as the polyamide filaments are situated inside the glass and reflections may have adverse effects. The reflection of daylight into the tunnel closely approximates the natural situation, so that conclusions for outdoor conditions can be drawn from a comparison of the test results from 2005 with the results from 2006. A distinctly worse test result (compared with the other experimental markings) would reinforce our caveat; if results were consistent with those of 2005, the doubts would be removed.

10 v: The marking 10 v was taken as a reference marking as it was tested both in 2004 and 2005. Re-testing of 10 v in 2005 showed that the experiment, with the sample sizes used, yielded reproducible results. Thus, this much-analysed marking should also enable valid conclusions about the effect of daylight on the effectiveness of the markings. Due to the lower contrast under the new experimental conditions, worse results than in 2004 and 2005 were expected.

15 v and 10 h: The results for these markings were worse (weak tendency) or significantly worse, respectively, than for 10 v. By including these markings in the test, it could be determined whether there was a change in the order of effectiveness of the markings or in the relationships between them, and whether differences between them increased or decreased as a result of light falling on the markings.

2.4.1.2 New experimental markings: reduction of area covered

10 v // 5 white: In this marking, developed from 10 v, the 20mm wide lines of 10 v are reduced to 5mm, spaced 10cm apart. Effectiveness was expected to be lower than for 10 v.

Dots: The marking “dots” is a reduction of the marking “small circles”, which in 2005 resulted in 0% wrong decisions. The proportion of area covered was reduced from 25% to 6.5%. However, this test is imperfect, as two variables (light and area covered) were altered at the same time.

2.4.1.3 New experimental markings: comparison black – white

So far, “Acrylic horizontal” was the only black marking. The brightness of black is constant, as black does not reflect any light and the perception of brightness is not influenced by the surrounding light. This property might be very important for the effectiveness of markings under different light conditions.

10 v // 5 black: This marking is identical to 10 v // 5 white, but instead of white tape, black tape is applied.

10 v black/white: This marking is a direct modification of 10 v but the 20mm wide lines are divided into 10mm wide black and 10mm wide white lines; thus there is an inner contrast and a doubly variable contrast to the outside, which should be optimal in both strong and weak light.

2.4.2 Markings tested

Table 4 and Fig. 10 give an overview over the markings, which were applied on panes 50cm x 100cm. The terms used to denominate the different markings are codes composed of the size of the gaps between the markings (e.g. 10cm), width of the lines (e.g. 5mm) and orientation (h = horizontal, v = vertical).

Table 4: Description of the tested markings. Area covered depends on the size of the markings and the distance between them. UV reflectance was no choice criterion and was measured later. Old test results (“Error”: flying towards the marked pane) from experiments in flight tunnel I (2004, 2005) are included for comparison.

Marking	**Description**	**Area covered**	**UV reflectance**	**Result (“error“) 2004/2005**
10 h	Horizontal stripes (white tape); 2cm wide; 10cm apart	16.7 %	yes	21.6%
10 v (reference marking; comparison with 2004, 2005)	Vertical stripes (white tape); 2cm wide; 10cm apart	16.7 %	yes	4.6% (2004) 6.7% (2005)
10 v black/white	Vertical stripes (white tape); lines divided along the centre line – 1cm black, 1cm white; spaced 10cm apart	16.7 %	yes	-
10 v // 5 black	Vertical stripes (black tape); 0.5cm wide; 10cm apart	4.8 %	-	-
10 v // 5 white	Vertical stripes (white tape); 0.5cm wide; 10cm apart	4.8%	yes	-
15 v	Vertical stripes (black tape); 2cm wide; 15cm apart	11.8 %	yes	11%
Acrylic horizontal	PLEXIGLAS SOUNDSTOP® with incorporated black polyamide filaments; horizontal; 2mm wide; 28mm apart	6.7 %	-	6.7%
Dots	Circles (white adhesive film); r = 9mm; arranged in a grid; distance between midpoints of the circles 82mm	6.25 %	no	-

10 h **10 v** **10 v black/white (10 v b/w)** **10 v // 5 black (10 v // 5 b)**

10 v // 5 white (10 v // 5 w) **15 v** **Acrylic horizontal** **Dots**

Figure 10: Markings tested in 2006

2.4.3 Reflectance of markings

In 2006, for the first time reflectance of the markings, including those used in 2004 and 2005, was tested at wavelengths ranging between 350nm and 600nm (Ch.2.2.1.2).

The following materials were tested:

- White adhesive film, used for “small circles” in 2006 and for “big circles” and “small circles” in 2005
- White tape, used for 10 h, 10 v and 10 v 5 white in 2006
- Screenprint white (Eckelt 541), used for “small squares” in 2005 (RÖSSLER 2005)
- Semi-transparent adhesive film, used for “coral” in 2004 (RÖSSLER & ZUNA-KRATKY 2004)

As shown in Fig. 11, markings of white adhesive film reflect more light between 410 and 600nm (mean: >80.6%; >61.1%) than the white screenprint (mean: 51.4%). As expected, reflection by the dull film is lower (mean: 26.6%). Radiation in the range of 350 to 400nm (UV, violet) was reflected to a noteworthy extent only by the tape (mean: 37.1%). Compared to reflectance >410nm, reflectance by the semi-transparent film was relatively constant also in the UV range (22.3%).

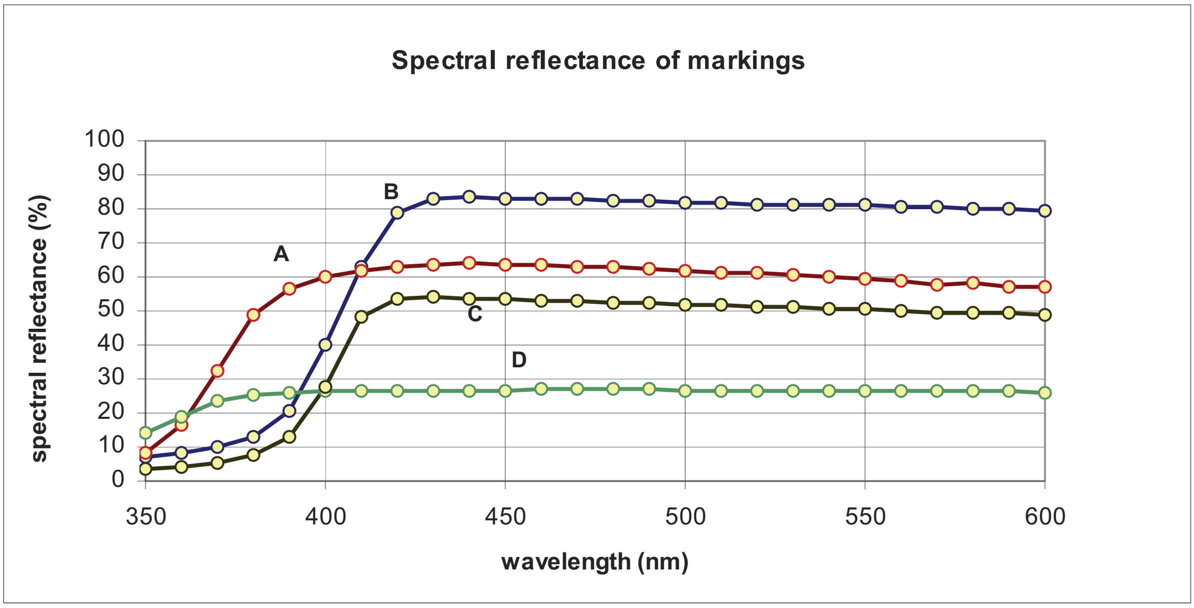

Figure 11: Spectral reflectance of different materials used as markings on glass panes in the experiments between 2004 and 2006. A: tape, white (white stripes); B: adhesive film, white (dots); C: screenprint, white (small squares, RÖSSLER 2005); D: semi-transparent film (coral, RÖSSLER & ZUNA-KRATKY 2004).

2.5 Transmittance of experimental panes

Depending on the materials and the thickness of the panes used, light transmission is variable. Thus, by comparing the optical properties of glass panes from different origins and of variable thickness, it must be possible to evaluate whether differences in effectiveness could be attributed to differences in transmittance. As shown in Fig.12, there are generally only small differences in transmittance between the panes; however, differences of 10-15% are possible for UV transmittance. In the UV spectrum, the acrylic pane differs greatly from the glass panes. Absorbers, added to increase durability, block wavelengths of up to 370nm completely, and only beyond 370nm does transmittance approximate that of glass panes. To control for this characteristic, an unmarked acrylic pane was also tested (Ch. 2.3.2)

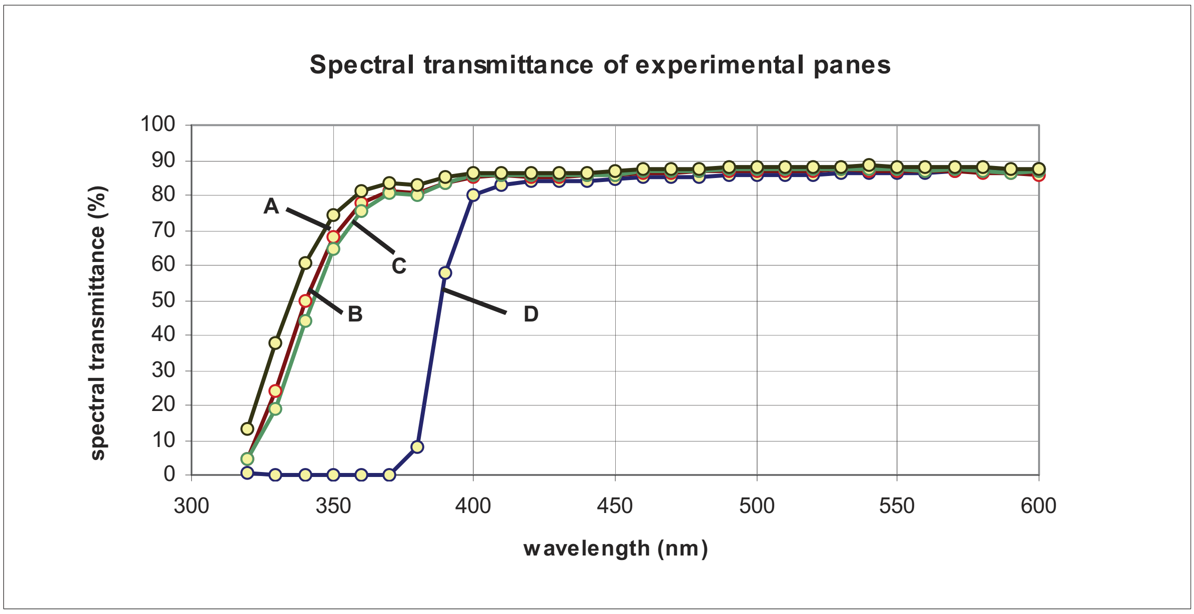

Figure 12: Spectral transmittance of four experimental panes of different origins and variable thickness. A: float glass ("coral" – 2004); B: float glass 4mm; C: float glass 5mm; D: acrylic glass with UV absorbers (PLEXIGLAS SOUNDSTOP®)

2.6 Light conditions during experiments

Half of the trials were undertaken before 9:00 AM. Timing of the experiments depends on the temporal distribution of captures by the ringing scheme, which is in turn dependent on the activity patterns of the birds. Thus the temporal distribution of the trials probably closely approximates natural activity–light intensity relationships.

Light conditions during the experiments were constantly measured by two photovoltaic sensors (Ch. 2.2.2)

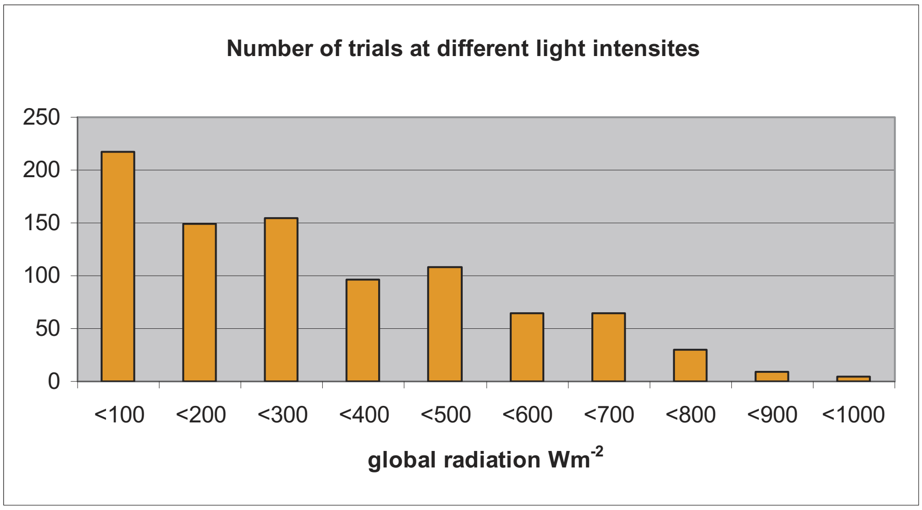

Figure 13: Number of trials under different light conditions (global radiation measured by pyranometer1). More than 50% of the trials (n=899) were conducted at light intensities ranging between 0 and 300Wm^{-2}.

2.6.1 Intensity of global radiation

Global radiation, measured by pyranometer 1 in a horizontal plane, ranged from 0 to 1,000Wm^{-2} during the investigation period; the median was in the range of 200-300Wm^{-2} (Fig. 13)[2] [3].

2.6.2 Light intensity behind the experimental panes

Illumination behind the panes, as measured by pyranometer 2 in a vertical measuring plane, ranged from 0 to 240Wm^{-2}. About one third of the trials took place at light intensities below 60Wm^{-2}, one third at 60-120Wm^{-2}, and one third at 120-240Wm^{-2}.

2.6.2.1 Light intensity and time of day

Light conditions behind the experimental panes are strongly dependent on time of day (i.e. position of the sun). Light intensity is lowest in the morning hours and highest at midday.

Typical time frames:

- 5:00 to 7:00am and 7:00 to 9:00pm – 65% of experiments <60Wm^{-2}
- 6:00 to 11:00am and 6:00 to 7:00pm – 50% of experiments 60-120Wm^{-2}
- 9:00 to 12:00am – 73% of experiments >120Wm^{-2}

2.6.2.2 Light intensity under sunny and overcast conditions

566 (60.3%) of the trials were conducted under sunny conditions, 314 (34.9%) under cloudy conditions; in 19 cases the sun was visible but partly clouded. Vertical structures (such as glass panes) that are exposed to the sun receive a relatively high intensity of radiation at low sun and a relatively low intensity of radiation at high sun. The majority of experiments with direct sunlight was conducted under relatively low sun conditions.

- Low solar altitude before 9:00am or after 5:00pm – 350 trials (61.8%)
- High solar altitude from 9:00am to 5pm – 216 trials (38.2%)

Direct solar radiation and light intensity behind the experimental panes are not necessarily correlated. Table 5 shows the light conditions, classified into three categories, that were measured behind the panes during 899 valid trials. A comparison with the data on cloudiness shows that both at sun and at cloudy skies 30-31% of the experiments took place at radiation intensities below 60Wm^{-2} and that in 21% of trials conducted in cloudy weather, radiation intensity at the back of the panes exceeded 120Wm^{-2}.

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[2] These data are of only limited validity for the illumination of the experimental panes because the sunlight component is higher than in the horizontal measuring plane at low solar heights and lower at high solar heights, as outlined by Lambert's cosine law (4.3.1.1.)

Table 5: Light intensity behind the panes under sun/no sun conditions

	Light intensity at the back of the panes Wm^{-2}			
	<60	**<120**	**>120**	
Sun, partly cloudy	176	210	199	**585**
No sun	97	151	66	**314**
	273	**361**	**265**	**899**

2.6.2.3 Relationship between global radiation and light intensity behind the panes

The graphs below show the diurnal variation in global radiation above and behind the experimental tunnel. Pyranometer 1 (A) in Fig. 14 measures radiation in a horizontal plane (maximum 907Wm^{-2} at 1:34pm). The measurements of pyranometer 1 are unaffected by reflections from the ground but influenced by direct solar radiation (above the tunnel). Clouds reduce measurements of global radiation by up to 70%. At the back of the experimental panes, pyranometer 2 (B), facing away from the sun, measures radiation in a vertical plane, with a high proportion of reflected light from the ground, vegetation etc. (blue line, with a maximum of 204.Wm^{-2} at 4:35pm).

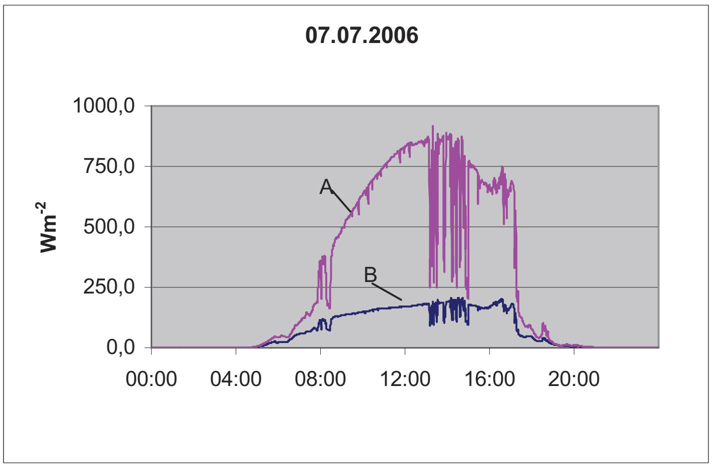

Figure 14: Diurnal variation of global radiation on 7th July, 2006, in Hohenau a. d. March. A: Pyranometer 1, arranged in a horizontal measuring plane, above the tunnel; B: Pyranometer 2, arranged in a vertical measuring plane, located at the back of the panes. Minimum values indicate passage of clouds.

During the morning and evening hours (5:00 to 9:00am and 5:00 to 8:30pm), or when there is no direct sunlight, there is a relatively close correlation between global radiation and light intensity behind the panes (Fig. 15). With increasing time of day (9:00am to 5:00pm) there is more variation in the data because the measured proportion of direct solar radiation increases with increasing solar height (Fig. 16).

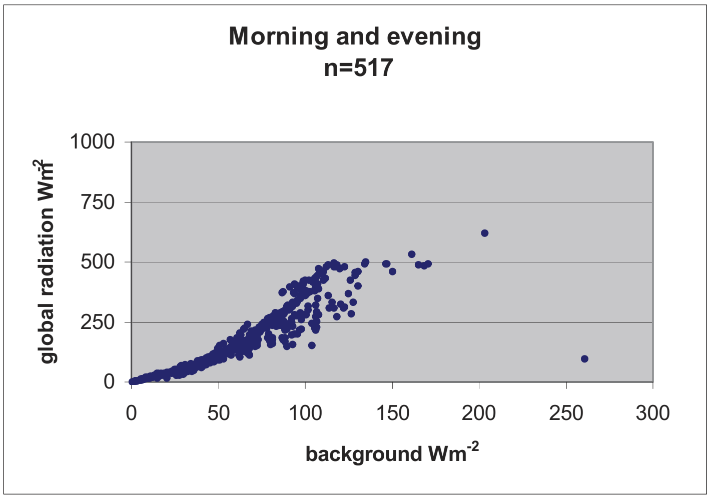

Figure 15: Relationship between global radiation (y-axis) and radiation at the back of the panes (x-axis); values expressed in Wm^{-2}. 5:00am to 9:00am and 5:00pm until sunset.

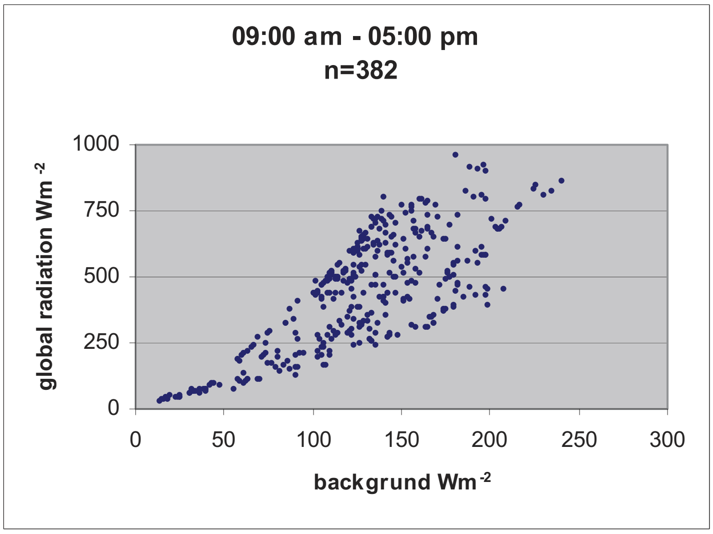

Figure 16: Relationship between global radiation (y-axis) and radiation behind the panes (x-axis); values expressed in Wm^{-2}. 9:00am to 5:00pm.

2.7 A model for determination of contrast

In order to address the question of contrast, an optical model was developed with which radiation density, as viewed by the bird, could be calculated. The model is currently in the validation phase. In the coming year, previous simulations are to be tested through selected measurements. It will then be possible to model different situations and light conditions, which can often not be measured, in order to draw conclusions about levels of contrast, effectiveness of specific levels of contrast and perception of birds in particular situations. Thus, it will be possible to make predictions concerning the effectiveness of specific markings without having to test all situations experimentally with birds.

The model is based on minute-by-minute values of light intensity above and behind the tunnel. The following variables are used:

- transmittance of the panes

- reflectance of the markings
- origin of the light (as determined by fish-eye photographs, Fig. 4) falling on specific sections on the experimental panes (direct sunlight, diffuse celestial radiation, reflections from the tunnel and the ground etc.)
- the measurement values of the two pyranometers at the time of the experiment

Incident radiation is different for each point on the pane. Using fish-eye photographs, the amount of global radiation and of radiation reflected by the environment is estimated.

All diffuse and reflected radiation falling on the glass panes can be calculated with the equation below.

$$I_{\mathrm{diff}} = 2 * \pi \int_{0}^{\pi/2} N(\theta) * \cos(\theta) * \sin(\theta) * d(\theta) * \theta \qquad \text{(vgl. 4.3.1.1)}$$

The contrast relevant for the bird is calculated as a quotient of the brightness of the markings and of the background. Thus

- Conditions in nature (for example light conditions during the experiments in 2006) can be modelled by inserting different values for the reflectance of the markings (as determined in the laboratory). That way, the contrast effect of a new, not yet experimentally determined marking can be rated.

- It can be attempted to relate the birds' behaviour in the experiments (recognizing and avoiding a marking or not) to the prevalent contrast.

2.8 Investigation period

Based on many years experience with capture rates, the experiments were planned for July and the first half of August. However, due to the extremely low breeding success of many birds as a consequence of the exceptionally wet and cold weather in May 2006, the number of birds captured in July was unusually low. The period of investigation had to be extended until the beginning of September. Unfortunately, the high number of captures in September could not be used for the experiments, as it was not possible to prolong the period of investigation as much as would have been desirable.

Thus, the investigation period lasted from 1st July to 4th September.

2.9 Study species

During the investigation period, all birds captured and ringed/checked by the ringing station that seemed capable of participating in the experiment were used as subjects. Juvenile birds whose plumage had not yet fully grown and birds that showed signs of exhaustion, as well as species that appeared unsuitable for the experiment due to their size were released immediately after ringing.

Birds used in the experiments included those that had been captured for the first time and were newly ringed, as well as birds that had already been captured during the investigation period (recaptures) and birds that had been ringed in previous years. After ringing or checking of rings by the ringing team, the birds are taken to the tunnel individually in small bags and participate immediately in the experiment). The order in which the birds are tested is dependent on the ringing activities. The species composition is typical for the locality. Table 6 shows the species list of birds that were used in 899 valid trials in 2005.39 species were included in the experiment. One fifth of the birds belonged to species that are typical victims of glass collisions in settlement areas, and all birds tested are potential collision victims in the open landscape.

Table 6: Species list for the 899 trials used in the analysis; species (39) and number of birds tested

Bird species		**Number**	**Bird species**		**Number**
Kingfisher	*Alcedo atthis*	3	Garden warbler	*Sylvia borin*	6
Wryneck	*Jynx torquila*	8	Black cap	*Sylvia atricapilla*	19
Great spotted woodpecker	*Dendrocopos major*	1	Chiffchaff	*Phylloscopus collybita*	2
Barn swallow	*Hirundo rustica*	2	Willow warbler	*Phylloscopus trochilus*	1
Wagtail	*Motacilla alba*	1	Blue tit	*Parus caeruleus*	1
Nightingale	*Luscinia megarhynchos*	4	Great tit	*Parus major*	19
Bluethroat	*Luscinia svecica*	16	Penduline tit	*Remiz pendulinus*	2
Stonechat	*Saxicola torquata*	2	Red-backed shrike	*Lanius collurio*	102
Blackbird	*Turdus merula*	9	Northern shrike	*Lanius excubitor*	1
Song thrush	*Turdus philomelos*	1	Starling	*Sturnus vulgaris*	15
Grasshopper warbler	*Locustella naevia*	11	Tree sparrow	*Passer montanus*	36
Sedge warbler	*Locustella fluviatilis*	12	Chaffinch	*Fringilla coelebs*	1
Savi’s warbler	*Locustella luscinoides*	4	Serin	*Serinus serinus*	1
Reed warbler	*Acrocephalus schoenobaenus*	56	Greenfinch	*Carduelis chloris*	4
Marsh warbler	*Acrocephalus palustris*	329	Goldfinch	*Carduelis carduelis*	12
Reed warbler	*Acrocephalus scirpaceus*	26	Hawfinch	*Coccothraustes coccothraustes*	1
Great reed warbler	*Acrocephalus arundinaceus*	51	Yellohammer	*Emberiza citrinella*	19
Barred warbler	*Sylvia nisoria*	6	Reed bunting	*Emberiza schoeniclus*	33
Lesser whitethroat	*Sylvia curruca*	1	unclear (unresolved recording error)		1
Whitethroat	*Sylvia communis*	80			
				Total	**899**

Capture rates in 2006 were far below the norm, owing to untypical weather conditions. In July, the number of captures was only 53% of the average of many years. According to a more detailed analysis, this is attributable not so much to the long winter or the high water events at the March River in April 2006 but rather to the very wet and cold May, which had enormous adverse consequences on breeding success of migratory birds arriving in March and April.

Cases of death: During the experiments, there was one mortality (great tit) by strangulation in the net (a very rare occurrence when mistnetting – 0.03%). There were no further injuries in the tunnel or at the experimental panes.

2.10 Preliminary tests and control trials

2.10.1 Preliminary tests

After construction of the new flight apparatus, it was necessary, like in the year 2004, to conduct preliminary tests[3]. It had to be reckoned that flaws or planning errors might become apparent, and that technical modifications might become necessary. The preliminary trials were conducted between 22nd and 30th June 2006.

1) Sporadic test flights during the construction period to enable early detection of potential major flaws that had not been considered (n = 10).

2) Sporadic test flights without panes and without nets; the birds fly unhindered out of the tunnel; the aim is to investigate the random distribution of their flight paths (n = 25).

3) Systematic test flights without panes, but with nets; to test the suitability of the nets without exposing the birds to the risks (n = 15).

All preliminary trials proceeded without problems; the birds' decisions for one of the two sides of the flight path were equally distributed, and there was no necessity to modify or adapt the experimental tunnel.

2.10.2 Control trials

Control trials serve to identify unrecognized errors during the experiments. It is tested whether there is a preference for one of the two sides (left or right) independent of the markings. The control trials are performed with two identical, unmarked panes and are distributed randomly in batches of ten trials between regular experiments.

2.11 Data analysis

2.11.1 Video analysis

The outcome of the experiments is recorded directly and videotaped at the same time for later re-checking. All video recordings are watched in slow motion. For the calculation of experimental results, only video data are used. In 171 cases (16.7%) the video documentation was at least of some avail or could rectify an erroneous recording.

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[3] In 2004, it unexpectedly turned out that the birds's choice of the left or right pane was strongly influenced by the position of the sun.

2.11.2 Analysed and discarded data

Only clear decisions for one of the two panes („left“, „right“) were used in the analysis and “in between” flights were discarded. Moreover, any flights that were discontinued and hesitant approaches, often along the ceiling or one of the side panels, were excluded. In cases where it became clear during the experiment that the trial would be unsuitable for analysis, an additional row was added in the protocol and the test was repeated with another bird. Cases where inconsistencies were not discovered until later during analysis of the videos (raindrops, fogged panes, unsymmetric incidence of light, open door etc.) were subsequently also discarded. Table 7 shows the number of discarded trials and the reasons for their rejection.

Table 7: Trials not included in the analysis

Reason for discarding data	**Number of cases**
Bird refuses to fly	29
Bird stops flying	9
Bird slows down in front of the net	4
Flight too hesitant	31
Reason unclear/not documented	13
Discarded later due to rain or fogged panes	33
Experimental error	7
Flight towards the middle	33
Total	**159**

2.11.3 Statistical methods

The data were analysed using binomial tests, chi-square exact tests and residual analyses with adjusted standardised residual values (HABERMANN 1973). Analysis was performed with SPPS 12.0.

3 RESULTS

3.1 Overview over the data

In all, 1,025 trials were carried out (Table 8), of which 899 yielded valid results and 126 had to be discarded. 866 trials could be assigned unequivocally to one of the sides (left or right), 33 flights towards the middle were also discarded. Left- or right-biases were controlled for by conducting 71 control trials. Thus, 795 trials were included in the analysis. 655 trials tested the effectiveness of the marked panes, 140 the basic question whether trials with the acrylic pane were influenced by the material (in particular, the UV-absorbers) and whether float glass is invisible to birds or can be perceived in some way.

Table 8: Structure of the 2006 data

Trials	**Number**	**%**		**Number**	**%**	
Total	**1,025**	100				
	▼		►	126	12.3	Invalid
Valid	**899**	87.7				
	▼		►	33	3.2	Towards the middle
Unambiguous	**866**	84.5				
	▼		►	71	6.9	Control trials
Test trials	**795**	77.6				
	▼		►	140	13.6	Other (UV, air)
Markings	**655**	63.9				

3.2 Experimental results

3.2.1 Overview over the results

Fig. 17 shows the results of all experiments, each with a sample size of 77 to 86. The markings are categorised into three groups according to their level of effectiveness (A to C). The results from the “float glass unmarked versus acrylic unmarked” trials (n = 68) and the “float glass unmarked versus open air” trials (n = 72) are grouped together in group D. Bars indicate the relative frequency of flights towards marked panes, unmarked acrylic panes and air, respectively; the corresponding percentage values are indicated above.

3.2.2 Markings

On average, 14.5% of flights were directed towards marked panes. All marked panes are effective; however, there are significant differences between the three groups (A, B and C) (chi square = 7.99; 2-tailed; p = 0.019). Effectiveness of the marking “Acrylic horizontal” is significantly better than the mean of all effective markings (residual analysis, adjusted, standardised residuals $\text{res}_{adst} = 2.1$; $p<0.05$)], while 10 h and 15 v (C) are significantly worse than average ($\text{res}_{adst} = -2.3$; $p<0.05$). PLEXIGLAS SOUNDSTOP® (“Acrylic horizontal”) is the only marking with an error rate below 10%.

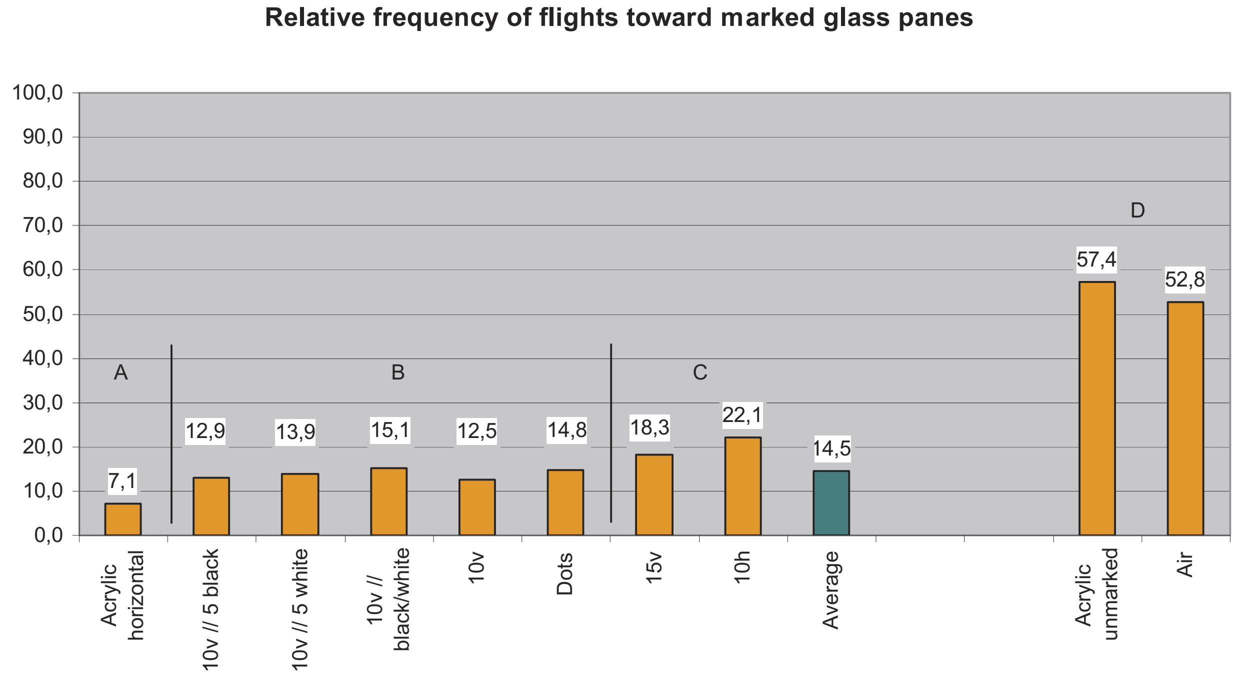

Figure 17: Relative frequency of flights toward marked glass panes in a choice trial with an unmarked reference pane. (B): markings of intermediate effectiveness; “Acrylic horizontal” (A) is significantly better than average, 15 v and 10 h (C) are significantly below average. Bars on the right (D): Number of flights towards an unmarked acrylic pane or an empty holding fixture (“air”), compared to an unmarked reference pane made of float glass.

3.2.3 UV-Absorbers in unmarked acrylic

In order to investigate the effect of the different material of the experimental pane “Acrylic horizontal”, an identical pane without incorporated polyamide filaments (i.e. a completely transparent acrylic pane) was tested against unmarked float glass. The results – 57.4% of flights towards the unmarked acrylic pane (39:29) – show no deterring effect of the material itself.

3.2.4 The “glass versus air” trial

In order to test whether transparent unmarked float glass is actually invisible to birds, one such pane was tested against an empty frame, i.e. open air. The test flights were randomly distributed at a ratio of 52.8% to 47.2%, with 38 flights towards the pane and 34 flights towards the open air.

3.3. Experimental results in relation to light conditions

The following questions ensued regarding the 655 analysed trials:

- Is efficacy of specific markings dependent on light conditions?
- Are some markings more effective, e.g. at dim light, than others?
- Which markings are best suited when only little vegetation but much sky is visible in the background?

Since the new experimental tunnel makes it possible to include and document different light conditions prevailing outdoors, we can now differentiate between results. Our sample sizes are just large enough to analyse the data according to three categories of light (Ch. 2.6.).

3.3.1 Effect of global radiation

Pyranometer 1 above the tunnel measures the light falling on a horizontal surface. The measured global radiation consists of light reflected from the clouds and the atmosphere, as well as direct sunlight. It has to be considered that the angle of incidence of direct sunlight is different for pyranometer 1, measuring in a horizontal measuring plane, and for the vertical panes. At low sun, the sunlight reaching the panes via the mirrors results in only low (horizontal) measurements by the pyranometer, despite strong illumination of the vertical panes. In contrast, at high sun conditions, the impact of the light on the panes is weaker than that measured by pyranometer 1.

An analysis according to three classes of intensity of global radiation (Table 9) did not show any significant influence of global radiation on the effectiveness of the markings (chi square =1.12; two-tailed; n = 655; p = 0.574; n.s).

Table 9: Distribution of flights towards the marked panes at different levels of brightness (global radiation measured on a horizontal surface), classified into three categories (below 250Wm^{-2}; 250 – 500Wm^{-2}; 500 – 1.000Wm^{-2}).

Markings	**Light intensity global radiation Wm^{-2}**					
	<250		**< 500**		**>500**	
	n	% Error	*n*	% Error	*n*	% Error
10 h	*43*	20,9	*21*	14,3	*13*	38,5
10 v	*48*	12,5	*15*	13,3	*17*	11,8
10 v b/w	*31*	19,4	*29*	17,2	*26*	7,7
10 v // 5 b	*58*	12,1	*13*	7,7	*14*	21,4
10 v // 5 w	*47*	12,8	*18*	16,7	*14*	14,3
15 v	*38*	21,1	*31*	12,9	*13*	23,1
Acrylic horizontal	*36*	8,8	*32*	8,3	*13*	0,0
Dots	*34*	16,7	*36*	12,5	*15*	15,4

3.3.2 Influence of illumination behind the panes

Pyranometer 2 measures the light falling on a vertical surface averted from the sun behind the tunnel. Half of the measured light is derived from the sky and the clouds, the other half from reflections from the ground and from vegetation. The vertical measuring plane enables a good comparison with the light that reaches the birds through the panes, so that a clear influence of light conditions on the results of the experiments can be shown.

The distribution of flight directions is not random with respect to light conditions behind the panes (Table 10). When separating the trials according to three light categories (<60 Wm^{-2}; 60-120Wm^{-2}; >120 Wm^{-2}), a significant deviation from an equal distribution of flight directions can be observed (Chi square exact two-tailed; Chi square = 11.55; p = 0.003; n = 655). Significantly more “errors” happen when light intensity behind the pane is below 60 Wm^{-2}, while significantly fewer occur at light intensities between 60 and 120 Wm^{-2}. Residual analysis showed that results were significantly worse under weak light conditions (adjusted, standardised residuals res_{adst} = -2.5; p < 0.01) and significantly better under intermediate light conditions (res_{adst} = 3.3; p < 0.001).

Table 10: Distribution of flights towards the marked panes at different levels of background illumination (diffuse celestial radiation and reflection from vegetation and from the ground, measured in a vertical plane)

Markings	**Light intensity behind the panes Wm^{-2}**					
	<60		**<120**		**>120**	
	n	% Error	*n*	% Error	*n*	% Error
10 h	*30*	20.0	*31*	22.6	*16*	25.0
10 v	*34*	14.7	*24*	4.2	*22*	18.2
10 v b/w	*14*	35.7	*35*	8.6	*37*	13.5
10 v // 5 b	*42*	14.3	*22*	4.5	*21*	19.0
10 v // 5 w	*32*	15.6	*24*	4.2	*23*	21.7
15 v	*27*	22.2	*33*	12.1	*22*	22.7
Acrylic horizontal	*21*	14.3	*30*	6.7	*34*	2.9
Dots	*14*	35.7	*46*	4.3	*21*	23.8

With the exception of the two markings that were considered less effective anyway (10 h and 15 v), all markings achieved error rates below 10% in the 60 – 120 Wm^{-2} category. It is noticeable that all results for markings that had already been tested during one of the previous years (in flight tunnel I) could be reproduced.

Table 11: Comparison of results from 2006 (flight tunnel II) and from 2004 – 2005 (flight tunnel I) at light intensities ranging from 60 to 120 Wm^{-2} behind the panes

	Flight tunnel I		**Flight tunnel II**
	2004	**2005**	**2006** Background illumination 60 – 120 Wm^{-2}
10 h	21.6		22.6
10 v	4.6	6.7	4.2
15 v	11.0		12.1
Acrylic horizontal		6.7	6.7

3.3.3 Effect of direct solar radiation

When the sun is shining, the sunlight is mirrored, equally distributed over the experimental panes, onto the markings. During the trials, it was recorded whether the sun was visible or covered by clouds. A comparison of trials during sunny and overcast conditions (Table 12) shows only random differences (Chi square = 0.175; 2-tailed; n=655; n.s.).

Table 12: Distribution of flights towards the marked pane during sunny and overcast conditions

	Sun		**No sun**	
	n	% Error	*n*	% Error
10 h	*47*	23.4	*30*	20.0
10 v	*33*	18.2	*47*	8.5
10 v b/w	*47*	14.9	*39*	15.4
10 v // 5 b	*36*	11.1	*49*	14.3
10 v // 5 w	*35*	8.6	*44*	18.2
15 v	*45*	13.3	*37*	24.3
Dots	*42*	13.2	*43*	17.9
Acrylic horizontal	*53*	7.1	*28*	7.0

4 DISCUSSION

4.1 Integrity of the experiments

One condition for the integrity of the experiments is that the trials are randomised.To check for methodological integrity, the relevant questions are:

- Were the experimental panes mounted equally frequently on the left and the right side?
- Are the results of control trials equally distributed on both sides?
- Are the results of the trials (independent of the varying efficacy of the different experimental panes) distributed equally on the left and right sides?

4.1.1 Equal distribution of experimental panes on the left and right side(s)

As it cannot be ruled out that small irregularities in tunnel symmetry or in the view behind the panes lead to a systematic preference of one side (left or right), the marked pane must be mounted equally frequently on the left and the right side. Table 13 shows the position of the panes in 795 trials with marked panes, unmarked acrylic panes (UV) and the empty frame (“Air”).

Table 13: Position of marked panes in 795 choice trials

Experimental pane	**Left**	**Right**	**Total**
10 h	38	39	77
10 v	38	42	80
10 v // black/white	45	41	86
10 v // 5 black	42	43	85
10 v // 5 white	39	40	79
15 v	41	41	82
Acrylic horizontal	44	41	85
Dots	43	38	81
Acrylic unmarked	39	29	68
Air	37	35	72
Total	406 (51.1%)	389 (48.9%)	795

4.1.2 Equal distribution of flights towards the left and the right side

Both the control trials (n=71) and the test trials (n=795), resulted in a nearly equal distribution of flights towards the right and towards the left. In total, the trials are perfectly evenly distributed on both sides (433 left, 433 right) (Table 14).

Table 14: Distribution of flights in 71 control trials (unmarked versus unmarked) and 795 valid choice trials (marked versus unmarked float glass; acrylic marked, acrylic unmarked and “air” versus unmarked float glass). Percentage values in parentheses.

	Flight direction		
	Left	**Right**	Total
Control trials	34 (47.9)	37 (52.1)	71
Test trials	399 (50.2)	396 (49.8)	795
Total	**433 (50.0)**	**433 (50.0)**	**866**

4.1.3 Equal distribution of "right" and "wrong" decisions on the left and on the right side

When considering the distribution of flight directions separately for "wrong decisions" (flight towards the marked pane) and "right decisions" (flight towards the unmarked pane), there is no deviation from an equal distribution.

Table 15: Distribution of flights in valid test trials (marked panes only, n=655) with 95 "wrong decisions" and 560 "right decisions". Percentage values in parentheses.

	Left	**Right**	**Total**
Marking ("wrong")	49 (51.6)	46 (48.4)	95
Reference pane ("right")	279 (49.8)	281 (51.2)	560
Total	**328 (50.1)**	**327 (49.9)**	**655**

As outlined in Ch. 4.1.1 and 4.1.3, the results of the 795 analysed trials are consistent and valid under the premises of the experiments. An analysis of the position of the experimental panes shows no deviation from an equal distribution. Neither for the 71 controls nor for all 795 trials, neither for "wrong decisions", nor for "right decisions" is there a deviation from an equal distribution of flights towards the left and the right. Consequently, methodological integrity is ensured.

4.2 Discussion of experimental results

4.2.1 Unmarked glass is not visible

Besides effects of reflections, one cause of fatal collisions with glass panes has been assumed to be that birds cannot detect glass Until now this has not yet been experimentally investigated. In a choice trial between unmarked float glass and an empty frame (3.2.4), it could be clearly shown that this assumption is justifiable and that birds indeed do not detect glass.

4.2.2 Consistently high effectiveness of "Acrylic horizontal" (PLEXIGLAS SOUNDSTOP®)

"Acrylic horizontal" (PLEXIGLAS SOUNDSTOP®) is the only marking which resulted in less than 10% wrong decisions (3.2.2). With an error rate of 7.1%, the 2006 result is virtually identical to the result from flight tunnel I in 2005; thus there is no indication that lateral incidence of light has any negative effects on the marking's effectiveness in reducing bird collisions. Furthermore, "Acrylic horizontal" is the only marking with statistically significant differences to the worst rated markings (15 v and 10 h).

In a supplementary choice trial between unmarked float glass and unmarked acrylic glass (Ch. 3.2.3), there was no avoidance of the unmarked acrylic pane. This confirms that the determining factor is not the material (plexiglass with added UV absorbers), but that the high efficacy of “Acrylic horizontal” can be attributed to the black filaments.

4.2.3 No differences between a wide range of markings of intermediate effectiveness

White markings are not more effective than black ones or vice versa. Neither is there any evidence of white markings being more effective than black ones when e.g. background light conditions are poor; or black markings being more effective at very bright light. Moreover, there seems to be no reason to assume that a combined black-and-white stripe is of advantage.

The latter might be due to the simple, fixed features of the divided (black and white) line tested (Fig. 2.4.2). Perhaps it would be possible to create contrasts within markings that are more effective. The order of effectiveness for those markings composed of 2cm wide white lines which were already tested in 2004 remained the same (10 v > 15 v > 10 h). It is inconceivable that the markings 15 v and 10 h achieve error rates below 10%.

4.2.4 Light conditions in the background make the difference

A differentiation of the data according to light intensities yielded no results that would be distinct enough, for the sample sizes used, to carry out single comparisons and suggest specific markings for specific situations. However, the results clearly show that all of the markings tested work very satisfactorily in “intermediate” light conditions (60 – 120 Wm^{-2}) and lead to a considerable reduction in collisions. In more extreme light conditions, particularly when illumination behind the panes is relatively low ($<60Wm^{-2}$), the effect is lower. It is surprising, but coherent, that this is also the case for white markings. Further experiments will be necessary to explain this and to derive practical recommendations.

4.2.5 Experimental conditions are crucial

Many results of this study are new and have not been determined at this level of differentiation in any other study on bird collisions. The methods adopted to address the question have a major influence on the results and their validity. The necessity of a video analysis was already discussed in RÖSSLER (2005). The importance of light measurements is demonstrated by a comparison of the overall results with the differentiated analyses of light conditions. The results also show that our sample sizes are already too small to test the particular suitability of individual panes e. g. for one of three categories of illumination.

At the moment it cannot be determined whether validity of the results might be influenced by the limited length of the tunnel. The factor in question is not so much the distance from which the markings are visible but rather the birds’ flight speed and whether it is comparable to the natural situation. Video analyses provide only little information about this, as it is not possible to record the birds’ spatial coordinates for each video *frame*. Possibly, the tunnel will be further advanced with respect to analysis of spatial coordinates so as to be better able to evaluate, for example, changes in the bird’s flight direction and acceleration.

Generally, many results of the Hohenau investigations from 2004 and 2005 were confirmed. The experiments show a high reproducibility, an important condition for the investigations. However, with sample sizes around n=100, it is not yet possible to distinguish between very efficient markings which elicit only very few “wrong decisions” in a high number of trials. The better the markings, the greater the sample size must be.

4.3 An analysis of the literature on light, perception and behaviour

At a meeting of experts in August 2005 in Möggingen, it was called for increased efforts to include basic research (visual perception and neuronal processing of visual stimuli) as an important component in applied research on markings for glass panes. Not least because of the great interest in UV effective markings, it was necessary to better integrate light parameters, physiological and psychophysical characteristics of birds in our work. Neither in KLEM's (1990) experiments nor in those by SCHMID & SIERRO (2000) or LEY (2004) were light conditions measured or systematically controlled.
Based on a literature research, an outline of factors in visual ecology of birds that have already been investigated will be given below. The main focus is on:

- Composition and intensity of the light
- Perception of light, brightness and colour
- Visual perception and behaviour

4.3.1 Intensity and composition of the light

Intensity and composition of the present or perceived light are different for any position in space and depend on radiance of the light source (radiant and reflecting objects) and on the angle of the light impinging on the viewer's eye from different sources. Light sources include the sun, blue sky, clouds, vegetation, the ground (or surfaces of water and snow), objects of anthropogenic origin etc.

4.3.1.1 Calculation of light intensity

Light intensity at a surface irradiated by a light source depends on the angle of incidence of the light, whereby Lambert's cosine law comes into effect:

$$I = Io \cos \theta \quad (1)$$

where I is light intensity, Io is intensity of incident light at a surface perpendicular to the direction of incidence and θ is the zenith angle of the light source. Energy is indicated in Wm^{-2}.

In nature, light comes not only from a light source, but also from numerous reflecting surfaces. The intensity of this reflected light (Ir) is dependent on the reflective properties of the reflecting surfaces and is calculated as

$$Ir = I * Refl \quad (2)$$

where I stands for the incident radiation impinging on the medium (molecule of the atmosphere, cloud, leaf etc.) and Refl is the reflective potential of the medium.

The intensity of diffuse radiation I_{diff} falling on the pane from all directions is an integral of the diffuse radiation density N impinging from all directions θ (zenith angle).

$$I_{diff} = 2*\pi \int_{0}^{\pi/2} N(\theta) * \cos(\theta) * \sin(\theta) * d(\theta) * \theta$$

4.3.1.2 Radiance of direct solar radiation and diffuse radiation

ENDLER (1993) measured spectral composition of light in forests in both tropical and temperate zones with a spectroradiometer. For this purpose, radiance was measured as flow of photon mass per steradiant. Radiance of direct solar radiation is greater than that of the sky, the clouds or the vegetation by a factor of $10^8 – 10^{10}$ (Table 16).

Table 16: Total radiance of different light sources indicated as light flow in μmol*m-2*s-1*sr-1. Fluctuations due to clouds and leaves: 45% (ENDLER 1993).

Light source	**Total radiance (μmol*m^{-2}*s^{-1}*sr^{-1})**
Sun	$1.648 * 10^7$
Clouds	689.7
Blue sky	101.1
Sunlit leaves	23.52
Leaves in shade	1.25

4.3.1.3 Composition of the light

The radiances discussed above do not differentiate between different spectral areas. Since colours and colour perception depend on different wavelengths of light, it is necessary to consider the spectral composition of the light. The light reaching an observer from a reflecting surface is dependent on

- the composition of the ambient light illuminating the surface
- the reflective properties of the surface (e.g. a leaf with a maximum spectral reflectance at 555nm)
- and the medium between the surface and the viewer (clear air, haze, fog).

The reflective properties of a surface normally remain constant, at least for longer periods of time, and except during foggy or hazy weather, the haze of the medium can be neglected (ENDLER 1993). Thus, our main focus is on the composition of the ambient light, which can vary greatly depending on location, weather and time of day.

Fig. 18 shows the spectral composition of direct sunlight, cloudy and clear skies, and of light reflected directly from the vegetation. The curves indicate major intensity differences, as well as differences in spectral composition. Compared to the white light reflected from clouds, the sun's spectrum is richer (redder) in the region of longer wavelengths. Blue sky is richer in shortwave light (bluer), leaves reflect more light of intermediate wavelengths, and bark reflects in the intermediate to long wave region of the visible spectrum. A considerable amount of UV light (<400nm) is present at both cloudy and clear skies but is largely absent inside the vegetation.

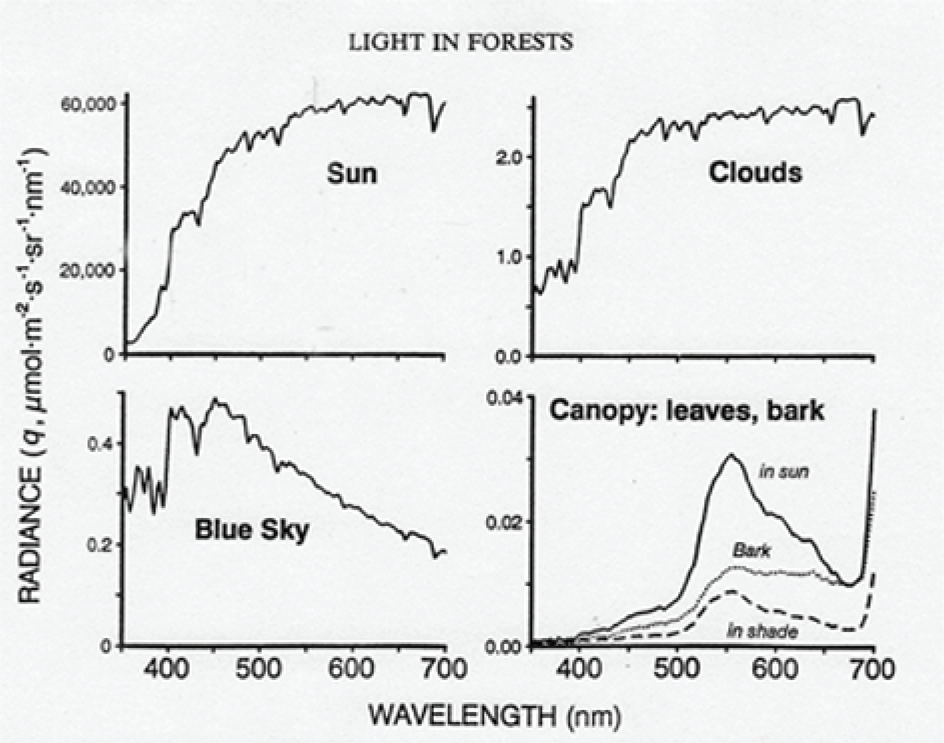

Figure 18: Spectral radiance of different light sources (ENDLER 1993).

Table 17: Spectral composition of the light (light environments) in different light habitats in forests (ENDLER 1993).

Light habitat	**Characteristics**	**Spectral composition of the light (light environments)**
Forest shade	No gaps; no direct sunlight little or no light from the open sky; all light is reflected or transmitted by the leaves	Rich in intermediate wavelengths of the visible spectrum;: greenish, yellow green
Woodland shade	Small gaps; no direct sunlight, mainly light from foliage, light from the open sky with higher radiance than light reflected from vegetation	Rich in shortwave and UV light (from the sky); bluish, blue grey
Small gaps	Solid angle 0.5° (corresponds to the sun Ø); light from the sun and from vegetation; no light from the open sky	Rich in longer wavelengths of the visible spectrum; reddish
Large gaps	Solid angle much greater than 0.5°; light from the sun and from vegetation, but also large amounts of light from the open sky	Mainly “white“ light
General shade (forest shade, woodland shade, small gaps, large gaps)		Mainly “white“ light
Morning light, evening light		Poor in intermediate wavelengths of the visible spectrum; purplish

ENDLER (1993) distinguishes between light habitats (e.g. shaded woodlands, small gaps) and light environments (spectral composition of the light). His investigations led to the differentiation of four light habitats, with regard to time of day and cloudiness, and five light environments (Table 17).

4.3.1.4 Effect of the variable ambient light on colour and contrast

The spectral composition of the ambient light has a crucial influence on the appearance of the object and its reflective characteristics – colour (hue), brightness and colour saturation (chroma). According to ENDLER (1993),

- The colour impression of a surface depends on its (constant) reflective properties and the (variable) spectral composition of the ambient light.
- As ambient light changes, contrasts between areas (or points) of different spectral reflectance also change because spectral radiance of these areas changes differently.
- The brightness of a surface with a particular colour impression depends on the similarity of its spectral reflectance and the spectral composition of the ambient light.
- As colour brightness of different areas (or points) changes, the achromatic contrasts also change.
- The degree to which colour impression and colour brightness of an area are influenced by the ambient light depends on the chroma (colour saturation). The weaker a colour's chroma, the greater are the fluctuations of colour impression and brightness with the ambient light.

4.3.2 Perception and behaviour

4.3.2.1 Photoreceptors and oil droplets

In vertebrates and insects, light perception occurs via photoreceptors in the eyes. Generally, the mechanisms in birds are quite similar to those in humans; however, there are fundamental differences in the photoreceptors. While humans have a trichromatic system[4] (three types of cones), birds possess four types of cones constituting a tetrachromatic system. Furthermore, birds have double cones for achromatic perception, which have important functions in motion vision. Oil droplets inside the cones serve as colour filters. Table 18 shows the functions of the retinal receptor system.

Table 18: Important components of the light receptor system and their functions in the bird eye

	Function
Rods	Crepuscular vision
Single cones, 4 types	Colour vision
Double Cones, 1 type	Photopic vision, motion vision, small structures
Oil droplets	Colour filters

4.3.2.2 Colour perception

Three of the single cone receptors show peak sensitivities (λ_{max}) in the visual spectrum of humans (S-,M- and L-cones for short-, medium- and long-wave sensitivities), the fourth type of cone extends light perception to the

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[4] Trichromatism in primates is an exception among mammals; in general, mammals have dichromatic vision.

wavelength spectrum of UV-A rays, or violet light (Fig. 20). UV-cones of *Passeriformes* show peak sensitivities at shorter wavelengths than those of *non-passeriformes* (Table 19).

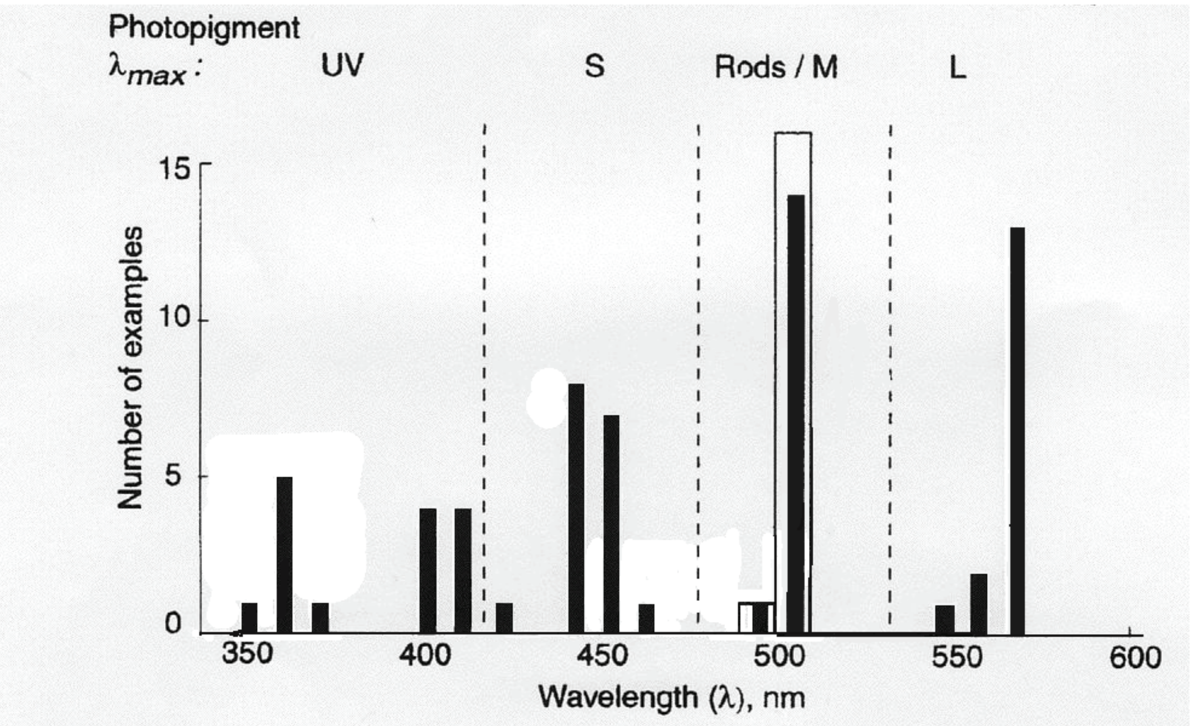

Figure 19: Number of spectral sensitivity peaks of 17 bird species with four types of cones in a spectral range of 350 to 600nm. Regarding sensitivity of the UV-cones, the species are split into two groups (approx. 360nm and approx. 400nm); the sensitivities of S-, M- and L-cones are very similar for all 17 species (OSORIO ET AL. 1999).

Fig. 19 (OSORIO ET AL. 1999) shows the two different sensitivities of UV-receptors, as well as the peak sensitivities of S-, M- und L-receptors in 17 species with low interspecific variability (BOWMAKER ET AL. 1997, VOROBYEV & OSORIO 1998).

Percentage distribution of cones in the retina:

VOROBYEV & OSORIO (1998) cite several authors and assume ratios of 1S:16M:32L in humans; 1UV:2S:2M:4L in the Red-billed Leiothrix *Leiothrix lutea (Passeriformes), and* 1UV:1S:1M:2L in the feral pigeon *Columba livia*. However, there may be large individual variations in the M:L ratio in humans. DILLENBURGER (2001) found that the level of variation differed between sexes, which might be explained by chromosomal mechanisms. So far it is not known how the ratios of the different photoreceptors influence perception. It appears, however, that colour perception in primates is not influenced (DOBKINS ET AL. 2000).

Table 19: Peak sensitivities of UV cones according to microspectrophotometer measurements by different authors (as cited in OSORIO ET AL. 1999)

	Peak sensitivity **λ_{max} of the UV cone nm**
Non–Passeriformes **(Non-songbirds)**	
Humboldt Penguin *(Spheniscus humboldti)*	403
Mallard *(Anas platyrhynchos)*	420
Pigeon *(Columba livia)*	410
Passeriformes **(Songbirds)**	
Blackbird *(Turdus merula)*	365
Starling *(Sturnus vulgaris)*	362
Blue Tit *(Parus caeruleus)*	367

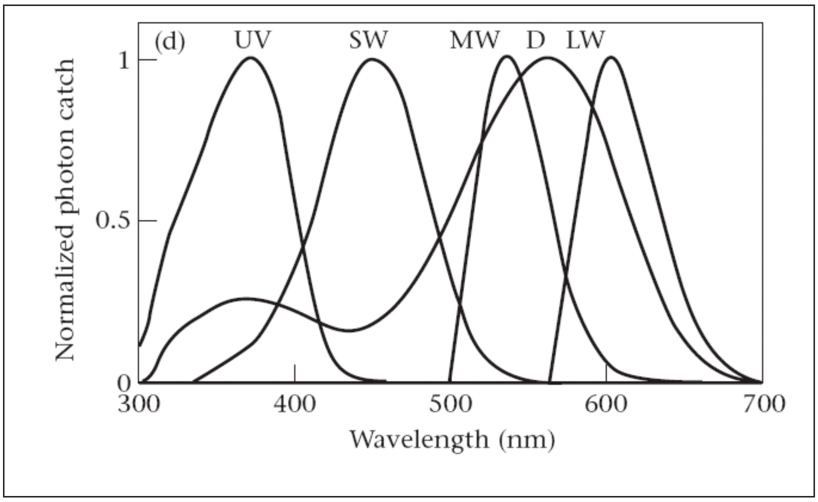

Figure 20: Standardised spectral sensitivity of the four single cones (UV, SW, MW und LW) and the double cones (D) in the Blue Tit (*Parus caeruleus*). (HART ET AL. 2000 as cited in STUART-FOX et al. 2003)

4.3.2.3 Chromatic contrasts

The reduction of chromatic contrast as a way of camouflaging, or the use of high chromatic contrast to deter predators (aposematism) are elements of visual appearance which are relevant to survival. Chromatic contrasts are of great significance for mate choice (sexual dichromatism), foraging, and recognition of objects with large-scale colour impressions (colour of regions, OSORIO ET AL. 1999).

SCHMIDT ET AL. (2004) found that for tanagers (Thraupidae) it is not the colour of the fruit per se (red, green, black, white), but the colour contrast between the fruits and the background that plays a key role in foraging. The birds did not show any preferences for red (artificial) fruits but selected red fruit against a green background and green fruits against a red background.

SCHAEFER ET AL. (2006) investigated the effect of chromatic and achromatic contrasts in crows. Red artificial fruits (1-2cmØ) with a high chromatic contrast to the (palm) vegetation were discovered from a greater distance than black artificial fruits with a low chromatic contrast. Many fruits that are dispersed by birds reflect UV light, which can be regarded as an indirect indication of an interrelation with UV-sensitive mechanisms in birds (cf. BURKHARDT 1982).

SCHAEFER ET AL. (2006) removed the UV-reflecting waxy bloom from blueberries (*Vaccinium myrtillus*), thus decreasing the chromatic contrast against an intermediate wavelength background (vegetation). Intact UV-reflecting berries were detected from a greater distance than manipulated berries with a low chromatic contrast that did not reflect any UV.

Primates, too, detect fruits in foliage that is very heterogeneous with respect to brightness (high achromatic contrasts caused by light and shade, low chromatic contrasts between the leaves) primarily by chromatic mechanisms (SUMNER & MOLLON 2000).

OSORIO ET AL. (1999) investigated the importance of chromatic and achromatic contrasts, as related to object size, with pecking experiments in day-old chicks. They found clear differences: with larger objects (5mm), blue and orange objects – creating chromatic contrasts against the grey background – were preferred, while white objects (creating achromatic contrasts) were ignored.

Chromatic contrasts in body colouration of animals and chromatic contrasts between body colouration and the environment are important in predator-prey relationships (camouflage, aposematism) and mating systems. Further examples are interactions between flowers and their pollinators or between fruits and seed dispersers. Here, UV reflectance can play an important role (BURKHARDT 1989). Chromatic contrasts are variable depending on the ambient light and the colour of the background, and since mobile organisms are flexible in their choice of environment, they possess the flexibility to display or hide chromatic signals. Another way of modifying signals is to expose different body parts to different light sources (ENDLER 1993, SANTOS 2005, HEINDL & WINKLER 2003).

4.3.2.4 Motion vision occurs in the long wave range of the visible spectrum

The double cones, the fifth kind of receptors in the bird eye, are responsible for motion vision in birds. These receptors have a high sensitivity in the spectral range of 500 – 650nm (Fig. 20). In numbers, double cones constitute 35 – 56% of the cones in terrestrial birds (HART 2001), but only 29 – 34% in seabirds (HART 2004).

Thus the long wave range of the visible spectrum is of greatest importance for motion vision.. Perception of achromatic contrast evidently happens faster than colour recognition; therefore motion vision and the perception of small structures belong, like photopic vision, to the achromatic mechanisms (OSORIO ET AL. 1999). For terrestrial birds[5], the double cones are of primary importance for the perception of moving light stimuli.

4.2.3.5 The importance of achromatic contrasts (light-dark contrasts)

For people, light-dark contrasts provide all visual information relevant to survival. The information loss of a black-and-white photograph compared to a colour photo is usually negligible. A moving object will be recognizable due to the changing light-dark contrasts. Only in the rare case of truly isochromatic[6] photographs is it not possible to distinguish, for instance, "a red sock from a green sock" (DILLENBURGER 2001).

Achromatic contrasts play a central role in motion vision in birds, i.e. in perception and control of their own movement and the recognition of moving objects. In Ch. 4.3.2.3, the importance of achromatic mechanisms for motion vision was described. Achromatic contrasts are also important in foraging – recognition of moving prey

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[5] This may not be the case for marine birds (in a „shortwave environment"). HART (2004) found lower amounts of double cones in several seabird species and concludes that the double cones, which are more sensitive in the long wave spectrum, are less useful for seabirds and may occur in a lower proportion as a result.

[6] Isochromatism: The sum of excitation states of all photoreceptors is exactly the same for e.g. two colours

and small objects. While chromatic contrasts are used in the recognition and differentiation of coloured surfaces, achromatic contrasts enable the recognition of contours and small structures.

In foraging tests with crows, achromatic contrasts led to slower detection (i.e. from a shorter distance) of (black) test fruits than chromatic contrasts (red fruits) (SCHAEFER ET AL. 2006).

The pecking trials with day-old chicks by OSORIO ET AL. (1999) described in 4.3.2.3 yielded contrary results for small (2mm) and large (5mm) objects. With small objects (achromatic contrasts), white objects were preferably pecked, and blue and orange ones were ignored. With bigger objects, the chicks preferred blue and orange objects – creating chromatic contrasts against the grey background – and ignored white objects (creating achromatic contrasts).

Birds of prey flying in the sky can certainly also be viewed as small moving objects with only achromatic contrasts. Attacks by sparrow hawks, hobbies etc. no doubt belong in the motion vision category. For the implications of this finding regarding effectiveness of silhouettes of birds of prey on windows, see Ch. 4.4.2.

4.4 Consequences of these theoretical considerations

It is not possible to draw inferences about avian visual abilities from human visual abilities. Nonetheless, many conspicuous colourations and contrasts in nature are very attractive to humans, too, and mechanisms of camouflage are also effective against humans. Nothing points to major differences in colour perception between birds and humans, except the difference in UV or violet receptors, enabling birds to perceive “colours” in the very short wave spectrum where people lack perceptive abilities. However, as the literature research in Ch. 4.3.2 shows, this sensitivity cannot be generalised.

The literature cited in 4.3.2. leads to a further dichotomy between “slow” and “fast”, chromatic and achromatic vision. The two receptor types (single and double cones) play different roles. Double cones, associated with motion vision process intermediate to long wave signals and initiate achromatic mechanisms. Thus, at least it cannot be ruled out that only intermediate to long wave signals are relevant for motion vision.

This has consequences for the development of effective markings for transparent panes. A development of an effective deterrent for birds in flight must take into account the mechanism of motion vision, using structures and wavelengths which are perceptible even during fast flight.

Strong contrasts in motion vision can be achieved by “black” and “white” colour tones, or indeed all very light and very dark tones (recognized by the achromatic mechanism as light or dark shades of grey) in the range of 500 to 650nm.

4.4.1 Silhouettes of birds of prey - a dead end

The idea of deterring effects of silhouettes of birds of prey is probably derived from LORENZ and TINBERGEN (c.f. SCHLEIDT 1961), who found in field experiments that certain morphological features (short neck, long tail) elicit flight responses in turkeys. SCHLEIDT (1961) repeated the experiments under laboratory conditions and

1. found that inexperienced turkeys (those in LORENZ and TINBERGEN’s experiments were not inexperienced) do not react specifically to particular shapes (cross, circle, stripes etc.).
2. showed that the flight response is correlated with the rarity of occurrence and declines with frequent exposure to the same silhouette

The experiments described were conducted with moving silhouettes. Based on the differences in stimulus perception described in Ch. 4.3.2 and the related differences in neuronal processing of stimuli, it can be assumed that attacking birds of prey and statically affixed silhouettes of birds of prey are perceived and processed differently.

The detection of an acute attack by an enemy (motion vision), is the responsibility of the achromatic mechanism, which has a very high temporal resolution (Ch. 4.3.2.5). The visual stimuli coming from a bird of prey (or other predator) attacking at high speed are 1) surprising, 2) fast-moving and 3) may possibly be perceived as a chain of individual images with structural properties that correspond to learned alarm cues. A silhouette affixed on a glass pane cannot altogether be assigned to this mechanism due to its size and immobility. It can be assumed that this motionless silhouette which 1) does not appear as a surprise, 2) does not move on its own and 3) as a large object triggers different signalling pathways that arrive in a different brain region. Thus, a silhouette is presumably processed as "object – obstacle in the flight path", which needs to be bypassed at a certain distance, like a branch or other obstacle. However, there is no far-reaching effect. Therefore, bird collisions may – and do – occur close to the silhouette. The ineffectiveness of this method has been proven several times (e.g. KLEM 1990, TRYBUS 2003).

4.4.3 UV markings – a dead end?

The "spiderweb effect" described by BUER & REGNER (2002) is another mechanism supposed to deter birds. Spider silk contains UV-reflecting substances to attract insects. At the same time, achieving a kind of aposematic effect (Ch. 4.3.2.3), birds are to be kept away from the webs. From this, BUER and REGNER derive the recommendation to develop "invisible markings" for glass panes on the basis of UV reflections to prevent collisions, since birds are capable of detecting UV light.

However, BUER and REGNER may be misinterpreting the works of BURKHARDT & MAIER (1989), BURKHARDT (1992) and others. They assume that the basic ability of birds to detect UV light is universally effective and they do not differentiate between different mechanisms of vision with different neuronal processing of signals. The ability of plants and animals to reflect UV radiation is normally associated with attractiveness and not deterrence, which may be different signal categories for different categories of vision (motion vision and "searching vision").

Up to now, it has not been investigated whether motion vision plays a secondary, a central or an exclusive role in the prevention of bird collisions with glass. If motion vision turned out to be of primary importance, it would be necessary to investigate birds' ability to detect short wave light in the motion vision mode. There is much indication that short wave light is not detected by motion vision (Ch. 4.3.2). If this were indeed the case, UV markings would in most cases be of only minor benefit

In an experimental set-up comparable to ours (but with artificial illumination), LEY (2004) performed 17 test series to investigate the effectiveness of UV-A reflecting or UV-A absorbing materials in reducing bird collisions. In 16 test series, there was no significant avoidance behaviour (in individual comparisons). One marking showed a significant effect. This test was repeated and resulted in 23.5% and (during repeat trials) 27% of flights directed towards the marked panes; hence effectiveness was considerably lower than e.g. for 10 v or "Acrylic horizontal". This fits with the hypothesis that the UV components of sensory stimuli are irrelevant in situations where motion vision is used. In the choice trials, the birds often depend primarily on mechanisms of motion vision, which may be of even greater importance under field conditions during fast movement.

4.4.4 Do effective markings exist?

4.4.4.1 What is effectiveness?

Our investigations, like those of KLEM (1990) and LEY (1994), are choice trials. In choice trials, a result of 50:50 means that the distribution is random, i.e. effectiveness is 0%. It would be mathematically incorrect to talk of 50% effectiveness in this case, or to speak of 90% effectiveness (or risk reduction) when the result is 10% flights towards the marked pane. It makes more sense to calculate a value of effectiveness by doubling the number of wrong decisions. This is, however, problematic because of statistical rules and can be regarded as valid only for results that have been reproduced several times. 25% wrong decisions thus mean a possible halving of mortality and not a reduction by 75%; 15% wrong decisions mean a possible reduction of mortality by 70% and not by 85%. For the sample sizes used in our experiments, reliable estimates at this level of accuracy are not possible.

A further constraint relating to sample size arises for the differentiation between very good markings: for a sample size of 100 trials, a statistically significant difference between e.g. five and ten collisions cannot yet be established, as this difference is within the realm of chance.

4.4.4.2 Significantly better than just effective

All markings tested in 2006 are effective. However, it is of much interest how effective they are and whether there are differences in effectiveness between markings. With sample sizes of 80 to 90 valid choice trials, it is already possible to differentiate between different classes of effective markings. The marking “Acrylic horizontal” achieves a significantly higher effectiveness than the average of the effective markings. The markings 10 h and 15 v, which are certainly effective, are nonetheless significantly less so than average (Ch. 3.2).

It can be concluded that there are many kinds of effective markings. However, the result “effective” cannot be a satisfactory goal as long as glass is increasingly used in bird habitats. “Effective markings” are effective for the avian fauna if they not only compensate for the increasing use of glass, but lead to a trend reversal of bird mortality through glass collisions. One aim of the Hohenau experiments is to develop markings which reduce wrong decisions in choice trials to five to ten percent. This is possible for the acrylic pane PLEXIGLAS SOUNDSTOP®. All markings (except 10 h and 15 v) achieve this goal at optimal illumination of the background; however this does not hold true for unfavourable light conditions.

4.4.5 Recommendations updated

It needs to be remembered that highly visible markings can significantly reduce bird collisions, but are far from preventing them. In view of the increasing use of glass, the effectiveness of the markings must be seen in perspective. It is no longer recommended to use the markings 15 v and 10 h. Prior to the start of the Hohenau experiments, the marking 10 h – horizontal white lines at 10cm intervals – was sometimes recommended, and it can also be seen on some buildings or noise barriers. However, horizontal lines are acceptable only if the lines are very close together, whereas vertical lines work reasonably well with up to 10 cm spacing.

At the moment, “Acrylic horizontal” can be recommended. There may still be factors which have not been considered enough in the experiments, and it has still not been sufficiently resolved why “PLEXIGLAS SOUNDSTOP®” achieved better results than other markings. However, there are all indications that this pane is highly effective at preventing bird collisions.

Furthermore, 10 v can be recommended. As expected, 10 v was less effective under a wide range of light conditions in 2006 than in flight tunnel I (flight tunnel I: 2004: 4.6%; 2005: 6.7%; flight tunnel II: 2006: 12.5%). At light intensities below 120Wm^{-2}, effectiveness was as good as under flight tunnel I conditions. Under most conditions, a two-third reduction in the number of bird casualties can be expected for markings of the 10 v type.

A combined black-and-white line is not recommended at the moment. In future test series, further emphasis will be put on investigating the effects of contrasts; after the 2006 results, this complex of questions is not yet tangible enough at the moment. For the time being, a reduction of the width of the lines to e.g. 5mm or of the size of the elements in general is not recommended. It needs yet to be determined which distances are relevant and which dimensions are processed in the motion vision mode.

Exclusively UV-effective markings are not yet on the market. The presently available data give reason to be sceptical whether the effectiveness will approach that of well contrasted “visible” markings. Generally, the results outlined in Ch. 4.3. rather point to the conclusion that motion vision does not detect UV light. Presumably, motion vision plays a central role in the recognition of glass markings. At the moment it is not yet possible to make recommendations about coloured markings.

Theoretically, high brightness, high chroma and wavelengths in the range of 500 to 650nm should be preferentially used. The effectiveness likely depends on achromatic components.

4.5 The next steps

4.5.1 Further experiments

As mentioned in Ch.1, the exploration of new and the optimisation of effective markings (e.g. minimal area covered, smallest object size etc.) will stay an important objective of our experiments in the future. This certainly also includes abandoning unsuccessful developments based on clearly negative results. In several cases, a negative result was expected, but the tests showed acceptable or even very good results. Typically, such results form the basis for very good new insights.

After the surprising results of 2006 – no differences between the extremes “white” and “black” – the question arises whether there is possibly no difference between these two markings and “grey”, either. This would confirm (but not explain) the effectiveness of the colourless semitransparent marking “coral” in the year 2004. In 2007, markings with a low “contrast potential” should also be tested, as results for black and white were not clear. Semitransparent markings work on a different principle from film, which eliminates certain wavelengths like a filter but does not change the contours of the image. UV markings probably work according to this λ-specific principle. Semitransparent film changes wavelength composition only slightly but disperses the light, which causes changes in the contours of the image and produces structural contrasts.

Furthermore, real “colours” are to be tested in the near future, and the variables “spectral reflectance”, “chromatic contrast” and “achromatic contrast” (high and low chroma, high and low brightness values) will play a role.

A different approach would be to create the impression of movement. This could be achieved by three-dimensional markings, or markings in front of and behind the pane which shift in relation to each other due to parallel motion axes.

5 SUMMARY

At the Biological Station Hohenau-Ringelsdorf, research on markings for glass panes that reduce bird collisions has been conducted since 2004. In the past, the focus was on perception of shapes; therefore the investigations were initially conducted under ideal light conditions. In order to get a more realistic evaluation of the effect of light in general and of contrasts in particular, a new flight tunnel was designed and constructed, which replaced the old experimental tunnel. The experimental apparatus is mounted so that it is turnable in a horizontal plane and can follow the path of the sun. Two vertical mirrors reflect direct sunlight symmetrically and evenly in parallel beams onto the panes. In “Flight tunnel II”, the effect of different markings can be experimentally investigated under daylight conditions. Global radiation and light conditions behind the panes are measured; the amount of illumination of the panes (reflection of the markings) is calculated with a model.

Under different light conditions during the 2006 trials, all markings proved to be effective. The results of the studies from 2004 and 2005 were largely supported. It was shown that the efficacy of the markings tested is more dependent on light conditions behind the pane than on the properties of the markings. At low background light levels ($<60Wm^{-2}$), the markings perform significantly worse, at intermediate light levels (60 and $120Wm^{-2}$) significantly better. At light intensities between 60 and $120Wm^{-2}$, the 2004 and 2005 results were reproduced almost exactly.

Unmarked glass and unmarked acrylic glass with no transmittance in the UV range were also tested. They are not detected or avoided by the birds. The experimental pane PLEXIGLAS SOUNDSTOP®, with 2mm wide black horizontal stripes spaced 28mm apart, was the most effective among the eight markings tested. Again, the markings 15 v (20mm wide, white vertical lines spaced 10cm apart) and 10 h (20mm wide, white horizontal lines spaced 10cm apart), which were already shown to be less effective in 2004, turned out to be less effective. In the intermediate range of effectiveness, there is a broad array of markings that are very similar in their effectiveness. At the moment, there is no evidence of differences in effectiveness between black and white markings, nor is there any indication of differences between stripes of 2cm and 0.5cm width.

In a literature analysis, this report summarises new findings about visual ecology of birds. It seems reasonable to suppose that motion vision in birds is restricted to the intermediate wavelength range of the visual spectrum and that UV vision is not compatible with motion vision. If it turns out that mechanisms of motion vision play a central role in the recognition of markings on glass, the main focus of further developments will be on achromatic markings (white, grey, black) and coloured markings in the range of 500 – 650nm, as well as on markings which are particularly conspicuous to motion vision (apparent movement through three-dimensional effects).

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