# PUPILLOMETRY OF GRAPHEME-COLOR SYNAESTHESIA

**Helle Gaare Paulsen and Bruno Laeng**

(Department of Psychology, University of Tromsø, Tromsø, Norway)

## Abstract

Pupil diameters of color-grapheme synaesthetes were measured with an infrared eye-tracker while Stroop-like alphanumeric symbols were passively viewed. Pupils dilated more when synaesthetes viewed incongruently-colored symbols than congruently-colored symbols or symbols printed in the standard black ink. The results show that the physiological measure of pupillary diameter can be used as a marker of the synaesthetic experience.

Key words: synaesthesia, Stroop effect, pupil diameter, color vision

## Introduction

The empirical, psychological, investigation of synaesthesia has a long history (e.g., Galton, 1880) and the use and discussion of cross-modal relations in poetry, literature, music and philosophical aesthetics is certainly older (Dunn, 1998). The first century of psychological research on synaesthesia has helped to establish several essential aspects of the synaesthetes' phenomenology: 1) private reports can be highly reliable (i.e., synaesthetes can repeatedly describe, verbally or by pointing to examples, the same stimuli with the same colors with a remarkable degree of within-subject consistency; e.g., Svartdal and Iversen, 1989); however, 2) these synaesthetic reports tend to have weak between-subjects consistency (i.e., the color pairings seem highly idiosyncratic, even among family members and identical twins; e.g., Smilek et al., 2001a).

Only until the current cognitive science and neuroscience research on (color) synaesthesia its perceptual nature has become clear. The early studies were mainly interested in assessing what the synaesthetes can "say" (i.e., their phenomenology or description of the experience), running into the problem of relying exclusively on the introspective method. Luria's (1968) case study on the prodigious memory of the synaesthete Solomon Shereshevsky is perhaps the first example of the modern investigation of synaesthesia, which goes beyond phenomenological report and explores in what ways synaesthesia can influence other cognitive phenomena (e.g., memory). The most recent studies have particularly cleverly circumvented the problem of relying exclusively on phenomenology by focusing, not only on what synaesthetes say, but mainly on what they can "do" with such experiences (i.e., their performance in visual attention tasks and memory; e.g., Smilek et al., 2001b, 2001c, 2003) as well as on which parts of the brain are active when synaesthetes report their private experiences (Nunn et al., 2002). Such an approach has led many to conclude that the nature of synaesthesia is perceptual. The main piece of evidence is that synaesthetic "photisms" can either assist or interfere with performance in visual tasks. In particular, there are demonstrable interference effects in naming the "objective" color of an object (e.g., a letter A) when at the same time this evokes a "subjective" or synaesthetic color (e.g., Mattingley et al., 2001). When the "objective" and "subjective" colors are incongruent (e.g., the letter B is printed in red but evokes also the color green) there is interference compared to when the colors are congruent (e.g., the B is in green).

Recently, crucial evidence for the perceptual reality of synaesthesia has been obtained by replicating well-known perceptual effects, like the ability of different colors to segregate regions or surfaces as figure and ground (Ramachandran and Hubbard, 2001). Remarkably, synaesthetes can identify and localize a target object (e.g., one digit 5) among distracting objects (e.g., several digits 2) more efficiently than non-synaesthetes, if the target and distractors differ by a synaesthetic color feature (e.g., Laeng et al., 2004; Palmeri et al., 2002). Apparently, the synaesthetic colors can "pop out" or cause an accelerated narrowing of attention onto a synaesthetically defined odd-man-out element of a scene.

One of the most common forms of synaesthesia, and the one we focused in the present study, is grapheme-color synaesthesia, where one specific grapheme elicits a specific color. This form of synaesthesia makes it possible to elicit Stroop-like situations where the (objective, externally observable) ink color of an alphanumeric symbol can differ from the (subjective, not externally observable) synaesthetic photism. The classic

Stroop effect is observed when subjects are requested to (typically) name the color of a color-printed word. When the color of the ink and the color denoted by the word are different, compared to when the two match, there occurs a slowing of response times (RTs). In synaesthetes, the same effect can be obtained by showing a single colored letter (e.g., Mattingley et al., 2001).

The present study also focuses on the investigation of the effects of synaesthetic Stroop-like stimuli. However, instead of using the traditional method of decision times or RTs, we examined a group of synaesthetes' physiological reactions by the method of pupillometry (changes in pupil size; Loewenfeld, 1993). As pointed out by Weiskrantz (1998), given that the eye pupil is controlled by the autonomic nervous system, it might be surmised that the pupillary response is generated by a "primitive", adaptive system that is especially tuned to the detection of novel occurrences; hence, pupillometry might be especially useful for assessing visual experiences where the verbal demands of psychophysical judgments are fraught. Weiskrantz et al. (1999) have also shown by testing a blindsight patient (GY) that the pupillary response occurs even when awareness is eliminated, although the size of the response is reduced.

Thus, it would seem that pupillometry could provide a privileged window over the subtle private experiences that characterize synaesthesia. As researchers have known for more than a century, variations in human pupil size occur in response to stimuli of interest to an individual (e.g., Dabbs, 1997) as well as difficult or engaging cognitive tasks (e.g., Kahneman and Beatty, 1966), despite constant illumination and no changes in ocular accommodation. In their seminal research, Hess and Polt (1964) showed that, during mental multiplication, the pupil diameter increased as the magnitude of the numbers became larger. These and other findings (Kahneman, 1973; Just and Carpenter, 1993) suggest that pupil size is a marker of processing load or use of attentional resources. However, pupillometry promises to throw light on much more than the investigation of attention.

In the present study, we explore whether pupillometry can be of help in elucidating the processing occurring during synaesthetic experiences. Specifically, we investigate the effect of exposure to Stroop-like stimuli in a small group of synaesthetic subjects. The situation is similar to the color-form interference paradigm, though in our experiments we did not request our subjects to name colors but simply to passively view the letters and numbers presented on a computer screen. On the basis of the above discussion, pupil size seems a reliable marker of processing load or, to use a term currently more in vogue, attention. Hence, "wrong" pairings of color and form should arouse attention and elicit physiological effects, and this should be measurable as changes in pupil dilation from conditions where the same symbols are colored congruently (for each synaesthete) or presented in their standard black print. Specifically, we would expect that incongruently-colored alphanumeric symbols would elicit larger pupil dilation than congruently-colored or the neutral black-colored symbols. In the present experiment, the incongruent items shown to a particular synaesthete were simply those items that were congruent for the other synaesthetes (by choosing those symbols which differed widely in color for the individuals in our group). Thus, each synaesthete served as a control subject for the other synaesthetes.

## Method

### *Participants*

Four grapheme-color synaesthetes, three females (ages 52, 55 and 61 years) and one male (age 23 years) were recruited as volunteers. Another subject (11 years old) was excluded due to lack of reliability in test and re-test of synaesthetic colors. Three of the participants were teachers at the music conservatory in Tromsø, and have had extensive training in music, both as professional musicians and as music teachers; one subject was a student in the psychology bachelor program at the University of Tromsø. For all of the synaesthetes, color vision was in the normal range according to the standardized results of the Farnsworth-Munsell 100 Hue Test (GretagMacbeth©).

### *Apparatus*

Pupil diameter was recorded from the participant's left eye by means of the Remote Eye Tracking Device (RED), built by SMI-SensoMotoric Instruments®. The recordings were then computed by use of I-View Software also developed by the SMI. The RED II can operate at a distance of .5-1.5 m and the recording eye tracking sample rate is 50/60 Hz – that is approximately every 20 msec, with resolution better than .1 degree. The eye-tracking device operates on the basis of determining the position of two high contrast elements in the eye: the pupil and the corneal reflection. According to an independent calibration procedure, given the constant distance from the screen, the pupil diameter was recorded with a definition of about 500 pixels per mm. However, given that changes in diameter were used in the interpretation of data, the exact eye diameter was not needed. Illumination of the room does not interfere with the recording capabilities of this apparatus. The coordinates of all boundary points are fed to the computer, which, in turn, determines centroids of the two elements. The vectorial difference between the two centroids is the "raw" computed eye position, which is in turn used to compute the pupil diameter based on the horizontal and vertical projections of the pupil's ellipsoid at the different sampled positions.

### *Materials*

Preliminary to the pupillometric measurements, each subject was requested to select the (synaesthetic) colors that corresponded to their photisms for each of the letters of the Norwegian alphabet, as well as for the numbers from 0 to 9. Specifically, all letters and numbers were presented in black in a Microsoft Word file, and the subjects were requested to select their own color nuances for each letter by using the font color feature of Microsoft Word 2000 software. The maximum numbers of Hues in the color palette is 256, with the same number of steps for Saturation and Luminance, thus yielding in total 256 × 256 × 256 colors. The stimuli were then prepared using Adobe Photoshop 7.0, and administered by use of the slide-show feature of ACDSee 32v2.4© software on a Pentium II computer (Windows 98). The stimuli consisted of three classes of letters and numbers: a) 6 letters and numbers in colors that each synaesthete had selected (the 'congruent' colors), b) the same letters and numbers in colors that three other synaesthetes had chosen (the 'incongruent' colors) and c) the same symbols in black (the 'control' or 'neutral' symbols). The letters "A", "B", "T" and "V" and the digits "3" and "4" were used, based on the fact that none of the synaesthetes had black or white as congruent colors for these and that, importantly, the colors differed for every subject. The symbols were presented centered on a flat, 17-inch monitor at font size 72. Given that any contrasting effects of color had to be avoided a white background was used (a region of color that surrounds another will tend to induce the opponent color in the surrounded patch). Similarly, white was the background when the subjects selected their colors using the Word 2000 software.

### *Procedure*

The laboratory was a windowless room; consequently the illumination (by artificial light) was kept constant throughout the experiments. This was important, as matching of color by eye in one set of illumination may turn into mismatch when illumination changes. Participants were seated at a distance of 72 cm in front of an image display computer. Their chins and foreheads were stabilized in a height adjustable headrest to minimize movements. The synaesthetes were first familiarized with the equipment used, and informed about the task. Then they were asked to place their head on a chinrest and gaze at the monitor while the experimenter adjusted the camera, zooming in to achieve a good resolution of the left eye's pupil on screen. At the beginning of each session a standard calibration routine was used. The eye tracker was calibrated using 9 fixation points, appearing as white plus signs on a blue background in a regularly spaced 3 × 3 matrix. The subjects were then told to fixate on the monitor while the letters were being presented on a white background, with blank white slides in between. The consistency in background color ensures that changes in pupil diameter can be attributed to stimulus differences rather than brightness differences. The display of stimuli and the recording of eye data were both controlled manually by the experimenter and an assistant using the ACDSee and I-view softwares.

## Results

### *Reliability of the Synaesthetic Colors*

Some synaesthetes show high color consistency over short, as well as long time spans. To assess color consistency in our subjects, the colors of the alphabet and digits were collected twice for all of the synaesthetes in our group.

Specifically, the colors of PM were collected in two, 4 months apart, sessions (c.f., Laeng et al., 2004). Correlation analyses showed highly significant relations for Hue ($R = .99$), Saturation ($R = .83$) and Luminance ($R = .92$). AL's colors were tested in two sessions, 18 months apart; correlation analyses confirmed highly significant relations for Hue ($R = .97$), Saturation ($R = .94$) and Luminance ($R = .97$). LG's colors' correlations were tested 13 months apart: Hue ($R = .94$), Saturation ($R = .96$) and Luminance ($R = .98$). PE's colors' correlations were tested 14 months apart: Hue ($R = .76$), Saturation ($R = .89$) and Luminance ($R = .93$).

### *Pupil Diameters*

A measure (in pixels) of pupil diameter was obtained in each trial by averaging the measurements of the horizontal and vertical coordinates that were recorded throughout the sampling cycle. Pupil samples in which the diameter was equal to zero – an indication of eye blink during the recording – were eliminated from the trials. Responses that exceeded a participant's mean by more than 2.5 SDs or that were shorter than 100 msec were treated as outliers and eliminated from the analyses. With these trimming procedures we eliminated about 2.5% of the pupillometric data. Analyses were based on participants' means for each of the three conditions (Black, Color Congruent, Color Incongruent). Pupillary responses of each synaesthete were given the same condition label based on each synaesthete's color photisms (i.e., as congruently-colored or incongruently-colored); instead, the pupillary

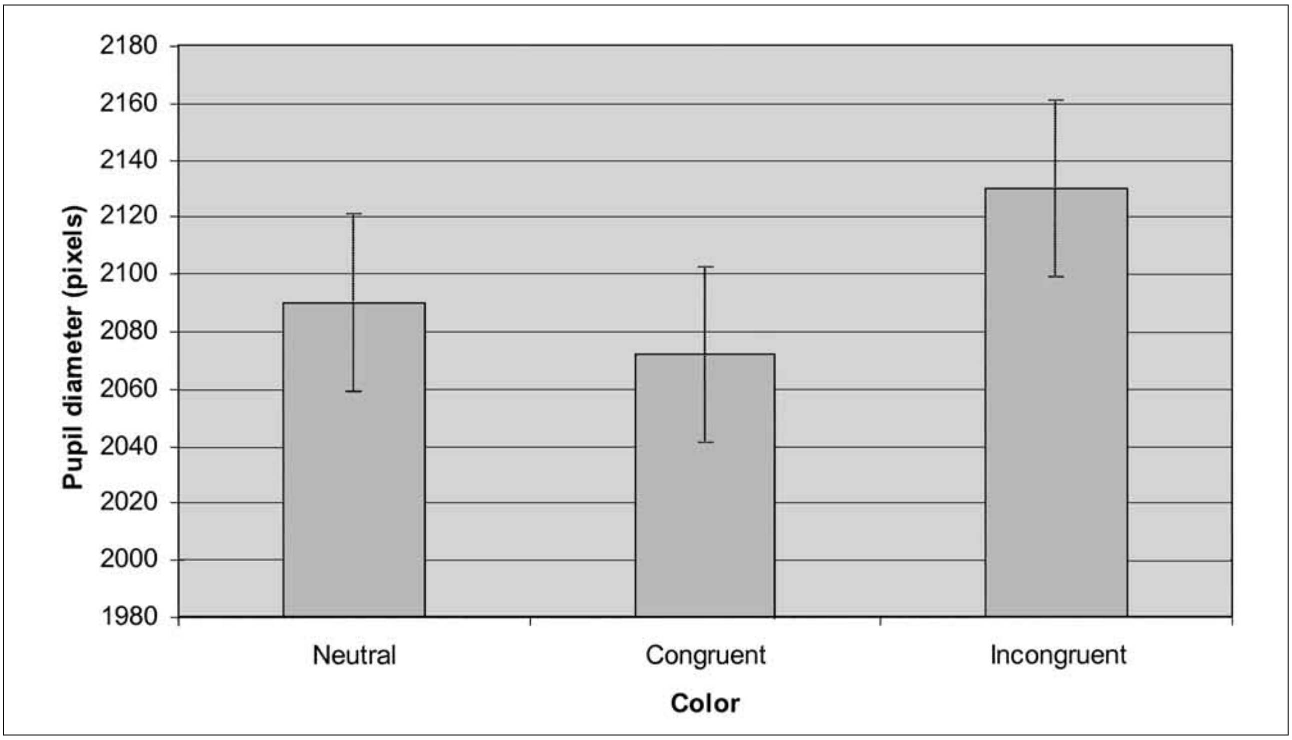


Fig. 1 – *Means (columns) and confidence intervals (bars) for the three Color conditions (Neutral, Congruent and Incongruent).*

responses to the black stimuli were labeled the same way for all subjects.

A repeated-measures ANOVA was performed with Color (Black, Congruent, Incongruent) as the within-subject factor and Pupil Diameter as the dependent variable. The analysis revealed a significant effect of Color, $F(2/6) = 5.3$, $p = .04$. Congruent colors yielded the smallest pupil diameters (mean = 2072, SD = 319), Incongruent colors the largest (mean = 2130, SD = 355), whereas Black ('neutral') symbols resulted in intermediate dilations (mean = 2090, SD = 350). Figure 1 illustrates the group averaged pupil diameters (the 95% confidence intervals were computed according to Loftus and Masson's, 1994, formula for within-subject designs).

Separate analyses were also performed for each individual synaesthete's pupillometric data. That is, repeated-measures ANOVAs were performed with Color (Black, Congruent, Incongruent) as the within-subject factor and each sample of Pupil Diameter as the random variable. All four participants showed a significant effect of Color, $4.2 < F < 86.92$, $.001 < p < .02$. Moreover, according to post-hoc tests (Fisher's PLSD), all subjects showed significantly larger pupil diameters in the Incongruent condition than in the Congruent condition, $.001 < p < .02$.

## Discussion

The pupillary responses of our synaesthetes were clearly different when they saw symbols colored according to their own synaesthetic experience than when viewing symbols colored differently (i.e., according the other synaesthetes' experiences).

Specifically, there were larger pupil dilations with the incongruently-colored symbols than with the congruently-colored ones. Thus, a physiological measurement as pupillometry is clearly capable to index the synaesthetes' reports of some colors having a privileged role over others.

The present study may represent the first pupillometric investigation of synaesthetic experience. The findings supported the hypothesis that the pupil's change in diameter can be used as an index of synaesthetes' private color experiences. Interestingly, reliable changes in pupil diameter were observed in the synaesthetes as a group as well as when each synaesthete was analyzed individually. Thus, pupillometry could offer a unique and valuable tool for exploring the private phenomenology of a synaesthete as well as, more generally, for psychological phenomena where verbal responses are difficult to obtain (e.g., in infants and non-human primates) or where the subject has no explicit knowledge of the information probed (e.g., in blindsight or amnesic patients).

For example, future pupillometric studies could investigate whether synaesthetic effects can be revealed by a synaesthete's pupillary response even in conditions where the synaesthete reports no "awareness" of subjective colors (similarly to blindsight patients' pupillary responses; c.f., Weiskrantz et al., 1999).

*Acknowledgements*. We thank Michele Miozzo for his comments on initial draft of the article.

## References

DABBS JM. Testosterone and pupillary response to auditory sexual stimuli. *Physiology and Behavior, 62:* 909-912, 1997.

DUNN KT. *Bright Colors Falsely Seen: Synaesthesia and the Search for Transcendental Knowledge*. New Haven: Yale University Press, 1998.

GALTON F. Visualised numerals. *Nature, 22*: 494-495, 1880.

HESS EH and POLT JM. Pupil size in relation to mental activity during simple problem solving. *Science, 140:* 1190-1192, 1964.

JUST MA and CARPENTER PA. The intensity dimension of thought: Pupillometric indices of sentence processing. *Canadian Journal of Experimental Psychology, 47:* 310-339, 1993.

KAHNEMAN D. *Attention and Effort*. Engelwood Cliffs: Prentice-Hall, 1973.

KAHNEMAN D and BEATTY J. Pupil diameter and load on memory. *Science, 154:* 1583-1585, 1966.

LAENG B, SVARTDAL F and OELMANN H. Does color synesthesia pose a paradox for early-selection theories of attention? *Psychological Science, 15:* 277-281, 2004.

LOEWENFELD IE. *The Pupil: Anatomy, Physiology and Clinical Applications.* Detroit, MI: Wayne State University Press, 1993.

LOFTUS GR and MASSON MEJ. Using confidence intervals in within-subject design. *Psychonomic Bulletin and Review, 1:* 476-490, 1994.

LURIA AR. *The Mind of a Mnemonist: A Little Book about a Vast Memory*. Cambridge, MA: Harvard University Press, 1968.

MATTINGLEY JB, RICH AN, YELLAND G and BRADSHAW JL. Unconscious priming eliminates automatic binding of colour and alphanumeric form in synaesthesia. *Nature, 410:* 580-582, 2001.

NUNN JA, GREGORY LJ, BRAMMER M, WILLIAMS SCR, PARSLOW DM, MORGAN MJ, MORRIS RG, BULLMORE ET, BARON-COHEN S and GRAY JA. Functional magnetic resonance imaging of synaesthesia: Activation of V4/V8 by spoken words. *Nature Neuroscience, 5:* 371-375, 2002.

PALMERI TJ, BLAKE R, MAROIS R, FLANERY MA and WHETSELL W. The perceptual reality of synesthetic colors. *Proceedings of the National Academy of Sciences, 99:* 4127-4131, 2002.

RAMACHANDRAN VS and HUBBARD EM. Synaesthesia: A window into perception, thought, and language. *Journal of Consciousness Studies, 8:* 3-34, 2001.

SMILEK D, DIXON MJ, CUDAHY C and MERICKLE PM. Synaesthetic photisms influence visual perception. *Journal of Cognitive Neuroscience, 13:* 930-936, 2001b.

SMILEK D, DIXON MJ, CUDAHY C and MERICKLE PM. Synesthetic color experiences influence memory. *Psychological Science, 13:* 548-552, 2001c.

SMILEK D, DIXON MJ and MERICKLE PM Synaesthetic photisms guide attention. *Brain and Cognition, 53:* 364-367, 2003.

SMILEK D, MOFFATT BA, PASTERNAK J, WHITE BN, DIXON MJ and MERICKLE PM. Synaesthesia: A case of discordant monozygotic twins. *Neurocase, 8:* 338-342, 2001a.

SVARTDAL F and IVERSEN T. Consistency in synesthetic experience to vowels and consonants: Five case studies. *Scandinavian Journal of Psychology, 30:* 220-227, 1989.

WEISKRANTZ L. Pupillary response with and without awareness in blindsight. *Consciousness and Cognition, 7:* 324-326, 1998.

WEISKRANTZ L, COWEY A and BARBUR JL. Differential pupillary constriction and awareness in the absence of a striate cortex. *Brain, 122:* 1533-1538, 1999.

Bruno Laeng, Ph.D., Department of Psychology, University of Tromsø, Huginbakken 32, Tromsø N-9037, Norway. e-mail: bruno@psyk.uit.no