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Table-tennis Under High Intensity Discharge (HID) Lighting

M.S. Rea and M.J. Ouellette

Introduction

High intensity discharge (HID) lamps are widely used for both indoor and outdoor applications, primarily because of their high luminous efficacy. The two most common types of HID lamp now specified in North America are high-pressure sodium (HPS) and metal halide (MH). In general, HID lamp choice will depend upon the importance of good color rendering relative to high luminous efficiency. The choice of the "orange" or "gold" HPS lamp generally represents an emphasis on energy conservation, whereas choice of the "white" MH lamp generally represents an emphasis on color rendering.

Flicker is another factor that is important but sometimes ignored in the choice of HID lamp type. Although HPS and MH lamps do not usually appear to flicker with 60-Hz alternating current, they do indeed vary, in different degrees, in their luminous output. Frier and Henderson¹ discuss the physical characteristics of the luminous modulation or flicker of HPS and MH lamps. Following calculation methods presented by Eastman and Campbell,² Frier and Henderson presented measurements of flicker index and percentage of flicker from HPS and MH lamps. They observed that with either calculation method HPS lamps flicker more and MH lamps flicker less than most HID lamps.

Frier and Henderson also describe the stroboscopic effect whereby objects appear to move discretely rather than continuously under flickering illumination. This effect depends upon the rate and amplitude of modulation as well as on the sensitivity of the observer to flicker. Their observations of a controlled, rotating table-tennis ball under different HID sources indicated that the stroboscopic effect was, not surprisingly, more noticeable under HPS than under MH. They also observed that the effect was largest when the ball moved across a large portion of the visual field; small angular movement produced minimal effect.

Based upon these observations, Frier and Henderson proposed that player performance at, say, table-tennis should not be seriously affected under lights

with a high flicker index (like HPS) because the angular motion of the ball would be small for players at each end of the table. Conversely, stroboscopic motion under the same lights should be more noticeable to spectators at the sides of the table because the angular movement of the ball would be much larger. Under lights with a low flicker index, like MH, the stroboscopic effect should always be small. They concluded, however, that even for sources with a high flicker index "at its worst . . . (the) stroboscopic effect will only be a nuisance or slight distraction."

The main purpose of the present study was to test the general hypotheses put forward by Frier and Henderson by measuring how flicker from HID lamps might affect player performance and spectator reaction at a typical ball sport. Table-tennis was chosen for testing because it was specifically discussed by Frier and Henderson, it was a convenient task to study, and the results should have general implications for predicting the magnitude of the stroboscopic effect at other dynamic tasks.

Two experiments were performed. The primary aim of the first was to measure the relative importance of several lighting parameters on table-tennis player performance; that of the second experiment was to evaluate table-tennis spectator reactions under the same experimental conditions. In both experiments light source (HPS or MH), line current (single-phase or triple-phase) and illumination level (33 or 1100 lx on the playing surface) were combined in a four-factor repeated-measures design. This simple experimental design tests the behavioral consequences of the full range of practical lighting conditions that might be used for table-tennis. This sensitivity analysis approach will help to establish whether subsequent experimental investigations would be appropriate; if no significant effects are discovered within the complete range of applications then it will be of limited practical interest to conduct more experiments on the same topic.

Experiment 1: Player performance

Ten young adult subjects (median age 19 years), one female and nine males, were paid participants in the study. All were right-handed, experienced table-tennis players, and had normal uncorrected vision as de-

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Figure 1—Plan view of experimental room. The labels a and b on the surface of the table represent the points used for measurement of flicker (**Table 1**). The table was shifted to the right by 0.6 m for operating MH sources.

finied by the battery of tests for the Keystone Opthalmic Telebinocular.

Figure 1 is a plan view of the experimental room. Nearly all objects in the subjects' fields of view (back walls, table, racquets) were painted grey ($\rho = 0.37$) to minimize changes in reflectance with changes in the spectral power distributions of the light sources. The subjects' t-shirts also were grey ($\rho = 0.22$). Commer-

	HPS		MH	
	Single phase	Triple phase	Single phase	Triple phase
Percent flicker	84 (95)	a) 11 b) 25	51 (38)	a) 14 b) 20
Flicker index	0.25 (0.29)	a) 0.035 b) 0.071	0.15 (0.11)	a) 0.041 b) 0.059

Table 1: Flicker of HPS and MH arrays measured at two locations (a and b, **Figure 1**). Values reported by Frier and Henderson¹ are shown in parentheses, and are associated with 250-W HPS and 400-W MH lamps operated on reactor type ballasts.

cially available white balls were used but not painted to avoid inevitable paint deterioration and possible changes in ball resiliency. A special 150-mm high net constructed of clear polyethylene with a 13-mm white strip along its top separated the two sides of play on the table-tennis surface. Monitoring equipment and the lighting control gear were outside the normal lines of sight during play.

Illumination was provided by five General Electric Lucalox 250-W HPS lamps or by five Westinghouse 250-W MH lamps, mounted "base up" in Spectra V, Series II, luminaires from Widelite Corporation. The luminaires were 2.8 m above the floor, had light emitting apertures of 61 × 61 cm and were arranged in a two-one-two array; for each light source array the table was positioned under the central luminaire (**Figure 1**). Horizontal illumination levels produced by the two kinds of light source were equated at either 33 lx or 1100 lx at the center of the playing surface. The HPS lamps were operated at 113–115 V ac, while the MH lamps were run at 118–120 V ac to help equate horizontal illumination levels on the playing surface. All lamps were operated with remote auto-transformer dimming ballasts. Baffles were attached to the under side of the HPS luminaires to help match illumination levels from each source at 1100 lx. Fixed mechanical filters were also attached to the under side of the HPS or MH luminaires to reduce illumination levels to 33 lx while maintaining constant spectral power distributions. Fans mounted on the ceiling approximately 60 cm from each luminaire prevented overheating when the mechanical filters were used. The uniformity of illumination on the table-tennis playing surface was within 19 percent.*

Lamps were operated on either single-phase or triple-phase line current. For the triple-phase condition, three groups of lamps were operated 120 degree out-of-phase with each other. **Figure 1** labels the luminaire phase groupings. Appendix A presents flicker measurements for both lamp types, operating on single-phase or triple-phase line current.

The experiment was conducted over a four-day period using a four-factor, repeated-measures experimental design.³ Subject pairs rather than individual subjects were treated as the random variable in the experimental design. All data from one subject pair were collected before running the next pair. There were eight possible experimental conditions, representing each unique combination of two light sources (HPS or MH), two illumination levels (33 or 1100 lx), and two supply currents (single-phase or

*Illuminance at 18 points on the table was measured under each of the different lighting conditions. Uniformity is defined as 100 S/M (in percent) where M is the mean of 18 measurements and S is the standard deviation about that mean.

triple-phase). On every day of the experiment the subject pairs performed 15 trials under each of the eight possible experimental conditions. In all, each subject pair performed 120 trials per day for four days. The experimental conditions were completely counter-balanced. The fifth pair of subjects performed the experimental conditions in the same order as the first pair, who had apparently changed their playing style mid-way through the experiment. The fifth subject pair was run as a possible replacement in the event that the change in strategy had affected the first pair's responses.

Special instructions were given to the subject pairs: (1) play should continue as long as possible, (2) return rate should follow an auditory metronome (0.8 Hz), (3) the same person serves, (4) the server is always at the same end of the table, (5) play stops when the ball (a) touches the net, (b) bounces more than once on one side of the table, (c) misses the table, (d) is missed by either player.

Player performance was monitored by two experimenters and by a video camera and recorder. Both experimenters simultaneously counted and then recorded the number of volleys; one operated a switch that controlled the timing unit of a PDP 11/73 mini-computer measuring and recording the playing times. One experimenter entered the number of volleys into the computer file after each trial. Occasional discrepancies in the volley counts of the two ex-

perimenters were resolved after completion of the experiment by examination of the video tapes.

A variety of statistical analyses were performed on the data obtained from the experiment. Both the duration of play and the number of volleys were used as dependent variables. Analyses were performed on averaged data obtained from the first four pairs of subjects as well as on all five pairs of subjects, both with and without logarithmic transformation of both dependent variables.** Very short volleys (less than two) were eliminated from the data in another set of analyses. Analyses using the number of volleys or the length of play gave statistically identical results, regardless of logarithmic transformations, the choice of subject pairs, or the exclusion of short volleys. Although there were some small differences in statistical significance, all the analyses gave essentially the same results. Only the main effect of illumination level and the three-way interaction for illumination level, line current (phase) and experimental sessions (days) reached statistical significance ($p \leq 0.05$). The three-way interaction cannot be interpreted and will be ignored. The significant difference in illumination levels is expected; there was, on average, a 7 percent drop in performance, as measured by length of play, at 33 lx relative to 1100 lx. In comparison, Whipple⁴

***This transformation provided approximately normal frequency distributions of volley counts and duration of play.*

Figure A.1.—Temporal illumination waveform, HPS array, measured at point a (see **Figure 1**).

Figure A.2.—Temporal illumination waveform, MH array, measured at point a (see **Figure 1**).

observed a drop of about 13 percent over the same levels, measured in terms of the number of strokes per point in a competitive game. Michaels and Reid⁵ observed a drop of about 19 percent, measured in terms of accuracy of return.

Experiment 2: spectator response

The lighting conditions were identical to those in the first experiment, as was the experimental design except that two sessions (morning and afternoon of one day) rather than four were conducted. Nine unpaid volunteers were recruited for this experiment. Two others played table-tennis for several volleys under each combination of the experimental variables while the nine spectators, five on one side of the playing surface and four on the other, watched the match. At the end of the volleys every subject completed the five questions presented in **Figure 2**. Spectators left the room between demonstration volleys to allow the experimenter to change the experimental conditions.

Five analyses of variance (ANOVA), one for each question, were performed on the spectator response data. **Figure 2** also presents, below each question, the statistically significant terms ($p \leq 0.05$) obtained from each ANOVA. **Figure 3** presents the average response for the questions in **Figure 2**. Although they may be important, it was difficult if not impossible to interpret the meaning of statistically significant session effects in this experiment; they will not, therefore, be

discussed.

Three major conclusions about spectator reaction can be gleaned from **Figures 2** and **3**. First, illumination level had a dramatic effect on spectator reaction: 33 lx was clearly disliked; unsolicited responses indicated that the illumination level was too low. Perhaps a longer exposure to low illumination levels would alter spectator reaction, but this was not tested. Second, the spectators' overall impressions (question 1) were better for MH than for HPS. Here again a longer exposure to HPS might have reduced this difference. Interestingly, light source and light level interacted to affect spectator responses to question 1. HPS was not so acceptable as MH at 1100 lx, although both were equally unacceptable at 33 lx. For question 2 dealing with impressions of color, spectator reactions were significantly different for the two light levels; the higher light level was more acceptable for color than the lower one. The main effects of light source and interaction between light source and light level were almost significant ($p = 0.075$ and $p = 0.078$, respectively) in the ANOVA for question 2, although spectral power distributions were unchanged during dimming. At the low illumination level impressions of color were equally poor for both sources of illumination, but acceptability was somewhat more enhanced (although not significantly) by increased illumination under MH than under HPS. Third, the stroboscopic effect was very important to the spectators. This is perhaps best illustrated by the significant light source

1. What is your opinion of this lighting condition?

	Source of variance	Chance probability (p)
1 Dislike		
2	I	≤ 0.01
3 Indifferent	S	0.02
4	P	0.01
5 Like	I $\times$ S	≤ 0.01
	S $\times$ D	0.03
	I $\times$ D	0.02

2. What is your opinion of the colour of the lights?

	Source of variance	Chance probability (p)
1 Dislike		
2	I	≤ 0.01
3 Indifferent	I $\times$ D	≤ 0.01
4		
5 Like		

3. What is your opinion of the brightness of this room?

	Source of variance	Chance probability (p)
1 Too dim		
2	I	≤ 0.01
3 Just right	I $\times$ S $\times$ D	0.04
4		
5 Too bright		

4. Describe any flickering of the ball.

	Source of variance	Chance probability (p)
1 Not noticeable		
2 Barely noticeable	S	≤ 0.01
3 Noticeable	P	≤ 0.01
4 Very noticeable	S $\times$ P	≤ 0.01

5. Describe any flickering of objects in the room.

	Source of variance	Chance probability (p)
1 Not noticeable		
2 Barely noticeable	nil	nil
3 Noticeable		
4 Very noticeable		

Figure 2—Spectator questionnaire. Only those probabilities of chance less than or equal to 0.05 are reported. Source of variance: I, Illuminance level; S, Light source; P, Line current (phase); D, Session. Dependent variable: Average response.

Figure 3—Average responses to spectator questionnaire (**Figure 2**). The labels S, P and I denote Light source, Line current phase, and Illuminance level, respectively.

by line current (phase) interaction in question 4; stroboscopic motion was very noticeable under single-phase line current with HPS lamps, but generally not noticeable with triple-phase line current or MH lamps. Unsolicited comments from the spectators indicated that "the ball was hard to see" with single-phase HPS lighting.

In total, spectators in this experiment found low illumination levels generally unacceptable and HPS less acceptable than MH. Two reasons for this were probably the poorer color perception and more noticeable stroboscopic motion of the ball produced by single-phase line current. (This second objection to HPS was minimal when the lamp array was operated on triple-phase line current.)

Remarks

In keeping with the hypothesis put forward by Frier and Henderson,¹ player performance at table tennis in this experiment was unaffected by stroboscopic motion. Although the rules of play were different from those employed in conventional table tennis, it seems very unlikely that stroboscopic motion induced by conventional HID sources would be a serious problem of player performance in this sport. Stroboscopic motion of the ball was not particularly noticeable to the

players, even under the worst conditions (single-phase HPS illumination). It is of limited practical interest, then, to extend investigations of table-tennis player performance in which stroboscopic motion is present.

Illumination level is important to player performance, as shown in earlier studies of table-tennis (Whipple, 1939; Michaels and Reid, 1948). Much like the performance decrements with reductions in illumination level indicated in those experiments, player performance deteriorated at lower illumination levels, probably because of reduced speed in processing visual information at lower adaptation levels.⁶ Although the mechanisms for performance changes due to variations in adaptation level will all be similar for on axis, static tasks and for dynamic, pursuit tasks like table-tennis, it may be valuable to develop a more detailed understanding of dynamic visual performance under more controlled experimental conditions.

Unlike the players, the spectators at the side of the playing surface found stroboscopic motion unacceptable. Frier and Henderson correctly hypothesized that the effects would be larger for spectators than for players, but they underestimated the problem. It is reasonable to extrapolate from these results and conclude that stroboscopic motion will be unacceptable

to spectators at any "ball sport."

Spectators were also very dissatisfied with the low illumination level. Clearly, illumination levels as low as 33 lx (that used in this experiment) are not acceptable for table-tennis. Although this level is well below the current recommended illumination levels for table-tennis of 200–500 lx,^{7,8} it may be of practical benefit to investigate the preferences of spectators watching table-tennis and other sports at higher illumination levels.

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APPENDIX A

Luminous flicker from light sources produced by alternating current can be described in several ways. Percent flicker is defined as:

$$\text{Percent flicker} = (L_{\max} - L_{\min}) / (L_{\min} + L_{\min}) \quad (\text{A.1})$$

where $L_{\max}$ = peak luminous output over time

$L_{\min}$ = minimum luminous output over time.

The flicker index is defined as:

$$\text{Flicker index} = (L_A - L_M) / L_A \quad (\text{A.2})$$

where L_A = total luminous output over time

L_M = mean luminous output over time.

Illuminances from the HPS and MH arrays, operating on single-phase or triple-phase line current, were measured at two locations (**Figure 1**) with a Hagner model S2 photometer using its external illuminance cell (**Table 1**). Photometer outputs, reported by the manufacturer to have a 400 μ s rise time, were recorded by a PDP 11/73 minicomputer. These measurements are shown in **Figures A.1** and **A.2** for HPS and MH lamps, respectively, at position a only. Values at the two locations differ owing to the relative proximity of the illuminance cell to the different light sources.

Discussion

The authors seek to determine the relative importance of stroboscopic flicker, color, and light level on performance in a table-tennis evaluation. Their controlled experiment shows that the effects of color and stroboscopic flicker are minimal but the effect of light level is substantial. Unfortunately, the use of baffles to equalize the Metal Halide and HPS lamp output and the use of mechanical filter, to reduce the light level from 1100 to 33 lx must certainly have changed the light distribution from one part of the luminaires. The table-tennis ball receives light from one part of the luminaire distribution and the background against which it is seen receives its light from another part of the luminaire distribution. Changes in the luminaire distribution therefore affect the contrast and visibility of the moving ball. Will the authors please indicate if such changes in luminaire distribution were evaluated and the results of that evaluation if it was made.

The authors have made, in my opinion, an unwarranted conjecture as to the reason that the player performance deteriorated at lower illumination levels. Nothing in this experiment, nor in the reference cited, relates the deterioration of performance in predicting the future position of moving objects to reduced processing speed at lower adaptation levels. My understanding of the literature relative to the prediction of the future position of moving objects is that two visual tasks are occurring and being processed simultaneously. One task is the "pursuit tracking" of the moving object and the other is the evaluation of the velocity and/or acceleration of background cues as they "flow by" in other portions of the visual field. A visibility model which seeks to predict our ability to evaluate accurately the future position of moving objects has not yet been proposed and will be very complex. We badly need a great deal of research in this

area and I hope that the authors will continue their work to determine the factors that cause the deterioration of player performance under various lighting conditions. As a result of the work done so far we can eliminate light source color and light source flicker as major contributors, but we can not yet explain the reasons for the difference in performance under the two light levels.

*Merle E. Keck
Lighting Consultant*

Authors' response

Mr. Keck questions our "unfortunate" use of mechanical filters to reduce illumination levels on the playing surface. The unstated implication is that, somehow, the distribution of light was confounded with illumination level to produce, alone or in combination with reduced illumination, the observed effects. This seems unlikely.

Our main concern was to have an even distribution of luminance on the playing surface, and great pains were taken to provide it under all experimental conditions. Further, to reduce luminance variations for the two light sources we painted all visual surfaces a neutral grey and even issued grey T-shirts to the players. We did not use a dimming system to reduce illumination levels on the playing surface because of the known color shifts in HID lamps operating at different voltages, another possible confounding influence on performance. Also, there is a highly compressed function that relates task contrast to visual performance. It is, therefore, unlikely that the relatively high contrast between the white ball and the grey background varied sufficiently to produce any large differential effects on performance as the ball moved through the visual field. In short, we were conscious of many possible confounding influences on performance and took care to minimize them. Thus, we feel confident that for this simulated, realistic task the observed effect was primarily a result of subjects playing table-tennis at different adaptation levels.

We were surprised at Mr. Keck's assertion that we made an "unwarranted conjecture" as to the reasons for deterioration of player performance and that the references cited do not support our conclusions. We suggest that he reread the second paragraph of the "Remarks" which is, we believe, a fair and even-handed interpretation. Mr. Keck should also remember that it was not the purpose of this experiment to develop a model of dynamic visual performance, and it seems unfair to criticize the paper for something the experiment was never intended to accomplish. Nevertheless, his concerns seem to lie, fundamentally, with the reason for reduced performance at lower illumination levels. Perhaps it is instructive to expand briefly on our interpretation of this effect.

It is a fact that the visual system responds more slowly with reduced illumination levels. We know too that visual performance for both static and dynamic tasks, using both speed and accuracy as dependent measures, deteriorates with illumination level. It seems reasonable to suppose then, that processing speed affects performance at both static and dynamic tasks. Although the mechanisms that cause these effects may be somewhat different when trying to process stationary tasks then when trying to process moving tasks. It seems highly unlikely that the biophysics will be radically different for static and dynamic tasks, as Mr. Keck seems to believe.

Finally, although Mr. Keck wishes to compliment our work by asserting that we showed spectral power distribution and flicker can be eliminated as major contributors to performance, we would not want the reader, nor Mr. Keck, to dismiss these effects altogether. Our results from the scaling experiment showed, however, that under a different set of viewing conditions spectator reactions were influenced by these factors. Some caution must, therefore, be exercised before dismissing spectral power distribution and flicker altogether. Under a different set of viewing conditions, one or both factors may be important to performance.