Consciousness and the double-slit interference pattern

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Abstract

A double-slit optical system was used to test the hypothesis that consciousness collapses the quantum wavefunction. The ratio of the interference pattern's double-slit to single-slit spectral power was predicted to decrease when attention was focused towards the double-slit as compared to away. Each test session consisted of 40 counterbalanced attention-towards and attention-away epochs, and each epoch lasted between 15 and 30 seconds. Data contributed by 137 people in 250 test sessions indicated that the spectral ratio decreased as predicted ($z = -4.36$, $p = 6 \times 10^{-6}$). Another 250 control sessions run without observers present tested hardware, software, and analytical procedures for potential artifacts; those data showed chance results ($z = 0.43$, $p = 0.67$). Meditation experience, psychological and environmental variables, and an electrocortical index of focused attention correlated with predicted changes in the interference pattern, supporting the consciousness collapse hypothesis.

Key words: consciousness, quantum wavefunction, quantum measurement problem

Introduction

> [The double-slit experiment] has in it the heart of quantum mechanics. In reality, it contains the only mystery. – Richard Feynman [1]

At the core of Feynman's mystery is the quantum measurement problem: Quantum objects behave differently when they are observed than when they are unobserved.[2] This is a problem because it strongly violates common sense. The doctrine of *realism* assumes that the everyday world is objective and independent of observation. But when it comes to a more fundamental level of reality, it appears that common sense is wrong.

The clash between naive realism and what quantum theory implies compelled virtually all of the founders of quantum mechanics to ponder the perplexing ontological and epistemological challenges presented by the measurement problem.[3-4] Some, like Pauli, Jordan, and Wigner, believed that consciousness was fundamental in the formation of reality.[5] Jordan wrote, "Observations not only disturb what has to be measured, they produce it .... We compel [the electron] to assume a definite position .... We ourselves produce the results of measurement."[6]

This strong view of the role of consciousness has echoed from von Neumann to d'Espagnat and from Squires to Stapp.[7-11] The significant nature of the proposition, and the prominence of those who have proposed it, has made the idea difficult to completely ignore, but to many it strongly challenges a gut feeling that the physical world was here, more or less in its present form long before consciousness evolved to observe it. Because of these challenges, many continue to resist the idea that consciousness could possibly play a role in the formation of physical reality.[12-13] One approach to eliminating the observer from quantum theory has been to sidestep the problem by simply declaring it a non-problem. That is, if observation increases our knowledge about a measured system, then "... from that position, the so-called measurement problem ... is not a problem but a consequence of the more fundamental role information plays in quantum physics as compared to classical physics."[14] Others deny that there ever was a problem: "Many physicists pay lip service to ... the notion that quantum mechanics is about observation or results of measurement. But hardly anybody truly believes this anymore—and it is hard for me to believe anyone really ever did."[15] Still others suggest that the only unambiguous way to avoid the role of the observer in physics is to deny the belief that we have free will.[16] While free will as a brain-generated illusion seems to be the prevailing assumption in the neurosciences today[17], that concept remains at odds with the only direct form of contact we have with reality – subjective experience – which includes the experience of deciding to believe that free will does not exist.

Philosophical and theoretical arguments aside, the double-slit experiment suggests a straightforward empirical way to study the measurement problem. It is based on (a) the fact that if information is gained – by any means –about the photon's path as it travels through the two slits, then the interference pattern will collapse and a single slit diffraction pattern will appear in proportion to the degree of certainty of the knowledge gained. And (b) if consciousness is not a localized side-effect of brain activity, but rather a non-localized property of the fabric of reality that we can modulate through focused awareness, then an individual asked to focus his or her attention towards a double-slit system with intent to gain which-path knowledge should be able to collapse the interference pattern to a small degree.

The second "if" above is of course a radical suggestion, but the possibility of a spatially extended consciousness is no more sensational than the spatial extension of entangled quantum states, which are mathematically well understood and confirmed to high degrees of experimental certainty.[18] Of greater importance, the concept is testable.

Three previous experiments have used optical interferometers to investigate the consciousness collapse hypothesis. Two employed a double-slit system[19] and one used a Michelson interferometer.[20] In the first study, a team at York University used a HeNe laser and double-slit apparatus to test unselected volunteers asked to "observe, by extra-sensory means ... monochromatic light passing through a double-slit optical apparatus, prior to its registration as an interference pattern by an optical detector."[21] That experiment was followed up at Princeton University with participants experienced at attention-focusing tasks, and they used a retooled version of the York optical system. The goal in both experiments was to shift the mean of a variable that measured the wave- vs. particle-like nature of the interference pattern. The York team reported a non-significant effect; the Princeton team reported a modestly significant mean shift ($p = 0.05$).

The third experiment involved a Michelson interferometer located inside a light-tight, double steel-walled chamber in the laboratory of the Institute of Noetic Sciences (Petaluma, CA, USA).[20] Participants directed their attention towards the interferometer from outside the chamber. The interference patterns were recorded once per second, and the average intensity levels of those patterns were compared in 30–second counterbalanced observation vs. control periods. After 18 planned test sessions, the results were in accordance with the prediction ($p = 0.002$). This outcome was primarily due to 9 sessions involving experienced meditators ($p = 9.4 \times 10^{-6}$). The remaining 9 sessions with non-meditators did not differ from chance ($p = 0.61$).

Control runs using the same setup, but with no observers present, also showed chance results. In sum, of three experiments directly relevant to the issue at hand, two supported the consciousness collapse hypothesis and one did not. Given the importance of the quantum measurement problem and the potential to inform it empirically, a new series of experiments was designed to reexamine the hypothesis using a double-slit optical system.

To avoid potential biases associated with selective data reporting, all completed test sessions in the six experiments described here, both exploratory and preplanned, were considered part of the experimental database and are reported. A half-dozen incomplete sessions conducted as brief demonstrations are not included, nor are a few sessions that were interrupted by power failures or computer glitches.

Experiment 1

Method

Apparatus

A 5 mW linearly polarized HeNe laser beam (632.8 nm, Model 25 LHP 151-249, Melles-Griot, Albuquerque, NM) passed through a neutral density filter (Rolyn Optics, Covina, CA), and then through two slits etched into a metal foil slide with widths of 10 microns and a separation of 200 microns (Lenox Laser, Glen Arm, MD). The resulting interference pattern was recorded by a 3,000 pixel CCD line camera, which had a pixel size of 7 x 200 microns and 12-bit A-D resolution (Thorlabs Model #LC1-USB, Newton, NJ). The camera was located 10.4 cm from the slits. This model laser was selected because it has a coherence length of more than a meter, and prior to its use in this study it had been in operation for several thousand hours, providing improved power output stability as compared to a new laser. A duplicate system was also constructed with similar components, for tests conducted outside the laboratory.

The apparatus was housed in a custom-machined aluminum housing, and painted flat black inside and out (see Figure 1). The laser and camera were allowed to warm up for a minimum of 45 minutes prior to running experiments. The experiment was controlled by a Windows Vista computer running a program written in Microsoft Visual Basic 2008 and augmented by software libraries from Thorlabs and National Instruments Measurement Studio 8.1.

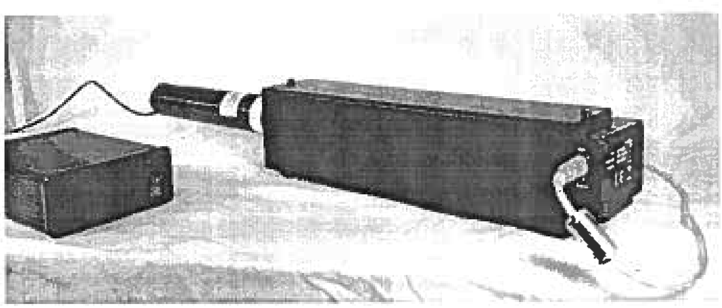

Figure 1: From the left, this shows the regulated power supply for the laser, the HeNe laser tube extending out of the optical apparatus, and the camera attached to the right side of the apparatus. The housing is a precision-machined aluminum box, painted flat black and optically sealed.

To measure changes in the wavefunction, the interference pattern recorded by the line camera was applied to a Fast Fourier Transform to quantify its two dominant frequencies: a higher frequency associated with the double-slit interference pattern (call this *D*), and a lower frequency associated with the diffraction pattern produced by each slit (*S*) (see Figure 2). The proportion of spectral power associated with the interference pattern was $D_p = [\frac{D}{D+S}]$, and with the diffraction pattern $S_p = [\frac{S}{D+S}]$. The ratio of these proportions, $R = D_p/S_p$, was the pre-planned variable of interest: it was predicted to decline as the wavefunction collapsed.

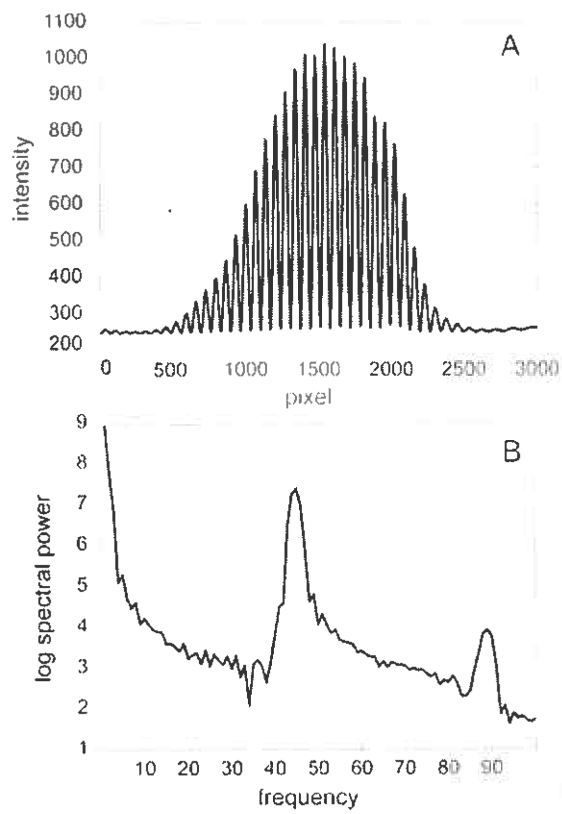

Figure 2. (A) Interference pattern recorded by the 3000 pixel line camera, averaged over 10,000 camera frames. (B) Spatial spectral power ($\log_{10}$), with double-slit power peaking at 45 and single-slit power at 1. The peak at 90 is a harmonic of the double-slit frequency.

Procedure

During a test session, participants were instructed to direct their attention towards the double-slit apparatus or to withdraw their attention and relax. Instructions for attention-towards epochs began with a computer-synthesized voice announcing, "Please influence the beam now," and for attention-away epochs with the phrase, "You may now relax."It was explained to participants that directing one's attention towards the apparatus involved a shift of the mind's eye, i.e. a purely mental act. Withdrawing attention meant to shift one's mental focus away from the double-slit and to think about something else.

Several methods were employed to help participants perform the rather abstract task of directing their attention towards two tiny slits located inside a sealed black box. First, for participants who knew nothing about the quantum measurement problem, each session began by playing a 5 minute cartoon animation of the double-slit experiment.[22] Then they were asked to (a) imagine that they could perceive photons as they passed through the double-slit, or (b) mentally block one of the slits, or (c) "become one with" the optical system in a contemplative way, or (d) mentally push the laser beam to cause it to go through one of the slits rather than both. Participants were invited to use one or more of these strategies, or to develop their own attention focusing technique.

The instructions directed the participants' attention towards or away from the optical system in 15-second epochs. A single test session consisted of 40 epochs presented in a counterbalanced order. The counterbalancing scheme consisted of five randomly assigned groups, where a group was either the assignment order **ABBA BAAB** or the order **BAAB ABBA**, where **A** and **B** refer to the two attention conditions. Test sessions began by collecting between 15 to 20 seconds of baseline data, followed by the 40 instructed epochs.

Participants sat quietly about 2 meters from the sealed optical apparatus (see Figure 3). They were instructed not to touch or approach the device at any time, and to ensure this in most sessions their movements were monitored by one or more investigators. The test sessions were conducted inside a solid steel, double-walled, electromagnetically shielded chamber at the Institute of Noetic Sciences (Series 81 Solid Cell chamber, ETS-Lindgren Cedar Park, TX). Electrical line power in this chamber is conditioned through a high performance electromagnetic interference filter (ETS-Lindgren filter LRW-1050-S1, Cedar Park, TX), and to further reduce electromagnetic interference the optical system and computer were powered by a battery-based uninterruptable power supply. It might be noted that in its original state this chamber is a rather intimidating steel box, so to make it more inviting the walls and ceiling were entirely covered with a soft, neutral fabric, anti-static carpeting was installed on the floor, and comfortable furniture placed in the room.

The computer presented a strip-chart display updated once a second with the spectral ratio R values. Participants were invited to look at the graph to gain near real-time feedback about their performance, or to view an alternative meter-type display showing the same information.

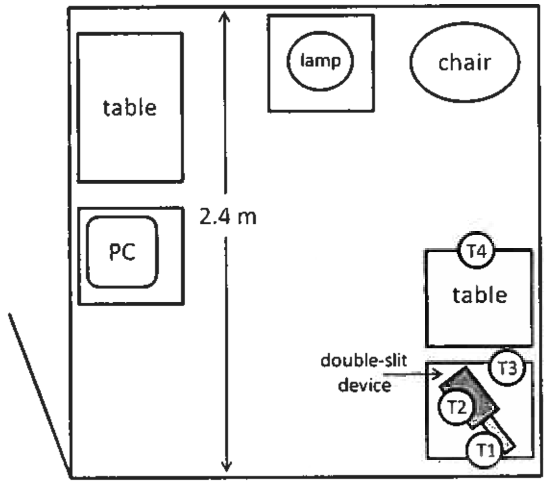

Figure 3: Room configuration for experiments conducted in the double steel-walled electromagnetically shielded chamber in the Institute of Noetic Sciences laboratory. The computer (PC) controlled all aspects of the experiment, including announcement of the attention-towards and attention-away instructions and acquisition of the interference pattern images from the camera on the double-slit device. In Experiment 3, thermocouples were placed on the laser tube (T1), on the double-slit housing (T2), near the housing (T3), and about 1.5 m in front of the participant (T4).

Analysis

The computer calculated R five times a second and stored the average of the last eight measurements once a second. To combine R across different test sessions, these values were normalized into standard normal deviates as $R_z = (R - \mu_R)/\sigma_R$, where μ was the mean of all R values in a given session, and σ was the standard deviation. A second data array of the same length (call it C) specified the attention-towards and attention-away conditions for each sample in R_z. From these two arrays, the differential statistic $\Delta_R = \overline{R_{zA}} - \overline{R_{zB}}$ was formed, where $\overline{R_{zA}}$ is the mean of R_z values collected during in the attention-towards condition, and $\overline{R_{zB}}$ the mean in the attention-away condition.

To assess whether Δ_R could have occurred by chance, a nonparametric randomized permutation procedure was employed. This avoided distributional assumptions about R_z and it took into account autocorrelation dependencies between successive R_z samples. To perform this analysis, the original array of R_z samples was circularly-shifted N steps, where N was randomly selected from 1 to the number of samples in the array. Using the new, time-shifted array, along with the original condition array C, Δ_R was determined, then stored, and this process was repeated 5,000 times. This generated a distribution of possible Δ_R outcomes, differing from the original only by when each test session effectively began. The statistic then used to assess Δ_{Ro} was $z = (\Delta_{Ro} - \mu_{\Delta_R})/\sigma_{\Delta_R}$, where the subscript o refers to the experimentally observed differential Δ_R, μ_{Δ_R} indicates the mean of the randomly permuted Δ_R values, and σ_{Δ_R} the standard deviation.

Hypothesis

The hypothesis (**H**) proposed that consciousness collapses the quantum wavefunction in a predictable way. Specifically, it proposed that (**H1**) the act of focusing attention towards a double-slit would cause *R* recorded during attention-towards epochs to decrease as compared to during attention-away epochs, (**H2**) this decline would take a few seconds to become maximally effective because it would take time for participants to switch their attention. (**H3**) the effects would be stronger in individuals who practiced some form of attention training, such as meditation, and (**H4**) prerecorded but unobserved events would not collapse until the act of observation took place.

Results

A minimum of 30 sessions were planned. Unselected participants were recruited by convenience, and 15 participants ended up contributing 35 sessions. At 15 sec/epoch × 1 *R*/sec × 40 epochs/session, this produced a total of 21,000 *R* measurements, half in the attention-towards and half in the attention-away condition. Twenty-four sessions were contributed by people who reported some meditation experience and 11 by non-meditators. No attempt was made to distinguish among different styles of meditation or to assess meditation ability.

All sessions took place in the IONS laboratory. Performance feedback was provided in real-time via the computer's strip-chart display. An additional 34 calibration sessions were run using the same hardware and software and with the apparatus located in the same location as during experimental runs, but with the computer's speakers muted and with no one in the chamber.

Figure 4 illustrates for one session the normalized *R* value and the counterbalanced condition assignments. The averages of the attention-away and attention-towards conditions are also shown, along with one standard error of the mean error bars (determined using the randomized permutation technique). Drifts and oscillations in *R* are exaggerated due to the normalization process and the graph's ordinate scale. The non-normalized *R* signal varied from its grand mean across the 35 sessions by an average of $v = 0.5\%$, where $v = [\max(R) - \min(R)]/\bar{R}$.

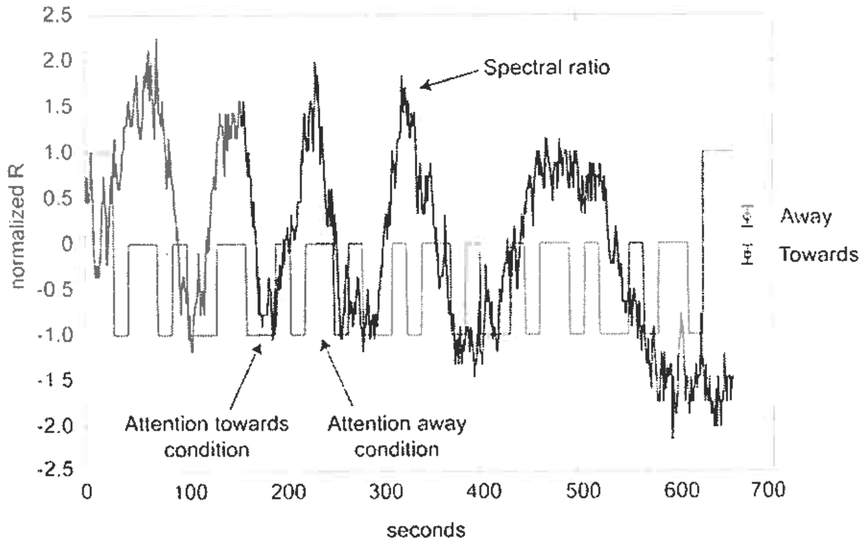

Figure 4. Example of normalized R data in one session, the attention conditions (attention-away periods at 0 on the ordinate and attention-towards at -1), and overall means by condition with one standard error bars. Normalizing the signal exaggerates its apparent variance. The original signal varied from its grand mean by an average of 0.5%.

Table 1 indicates that pooled over all sessions, the spectral ratio declined modestly in accordance with **H1**, and it was more negative for meditators than for non-meditators, as predicted by **H3**. Control tests resulted in a slightly positive result. Table 1 also displays *effect size* for each condition, where $es = z/\sqrt{N}$, and N = number of sessions. Effect size is a convenient way to compare the magnitude of effects across different datasets because it is independent of sample size. From this perspective, meditators produced effects 2.5 times larger than non-meditators. The effect size for all data combined is similar to those commonly observed in many behavioral and social science experiments, and regarded by rule of thumb as a "medium" effect size.[23]

	Sessions	*es*	*z*	*p*	*z* lag-2	*p* lag-2
All sessions	35	-0.26	-1.56	0.06	-1.84	0.03
Meditators	24	-0.32	-1.58	0.06	-1.64	0.05
Non-meditators	11	-0.13	-0.43	0.34	-0.87	0.19
Controls	34	0.15	0.85	0.80	0.85	0.80

Table 1. Results of Experiment 1. Effect size *es* is in terms of magnitude of the effect per session, z expresses the outcome of comparing R between the two attention conditions as a standard normal deviate. p is the one-tailed probability of z, and "lag-2" is the same analysis with R is lagged two seconds after the change of the attention condition.

The "z lag-2"column in Table 1 refers to a lag-lead analysis, which was used to test **H2**. This result of this analysis is illustrated in Figure 5. The abscissa in the figure shows the effects of time-lagging R with respect to the onset of the attention condition assignments. That is, *lag 0* refers to R recorded in time synchrony with the onset of the attention-towards or attention-away assignment, *lag-1* refers to the same analysis but with R *lagging* one second after the condition assignments were announced, *lag+1* to the data *leading* one second before the condition announcements, and so on. As predicted by **H2**, the figure shows that for all experimental data z becomes more negative when lagged a few seconds. By contrast, the control test data somewhat remained positive and relatively flat across 10 seconds of lag/lead. From the plot it can be seen that the optimal lag length was about two seconds, so Table 1 and subsequent tables summarize this analysis for lag-2.

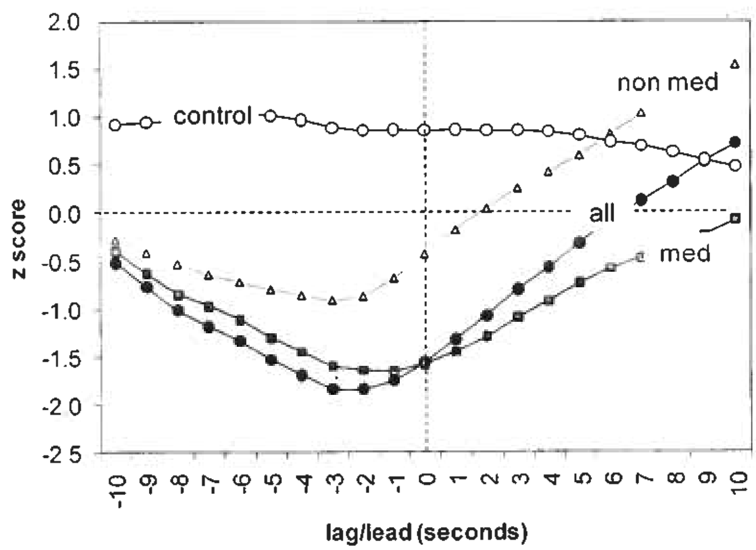

Figure 5. Z scores for lag/lead analysis. Lag 0 refers to R synchronized with the beginning of the attention conditions. Negative lags refer to R after changes in attention assignments, and positive lags to before such changes.

From the signal shown in Figure 4, one may wonder whether the primary effect in this study was due to slow drifts and oscillations (although this was unlikely due to the counterbalanced condition sequence which was randomly assigned in each session). To explore this possibility, R was smoothed with a 15-sample moving linear regression (one sample per second), then the difference between the original signal and the smoothed signal was determined to form the residuals (see Figure 6). When similarly formed residuals from all sessions were combined and analyzed using the permutation technique, the result at z(lag 0) = -2.8 and at z(lag-3) = -4.2, as shown in Figure 7. This suggests that drifts and oscillations were not responsible for the observed results. However, to avoid complicating the analysis, rather than using residuals the normalized unfiltered signal was used in all subsequent analyses.

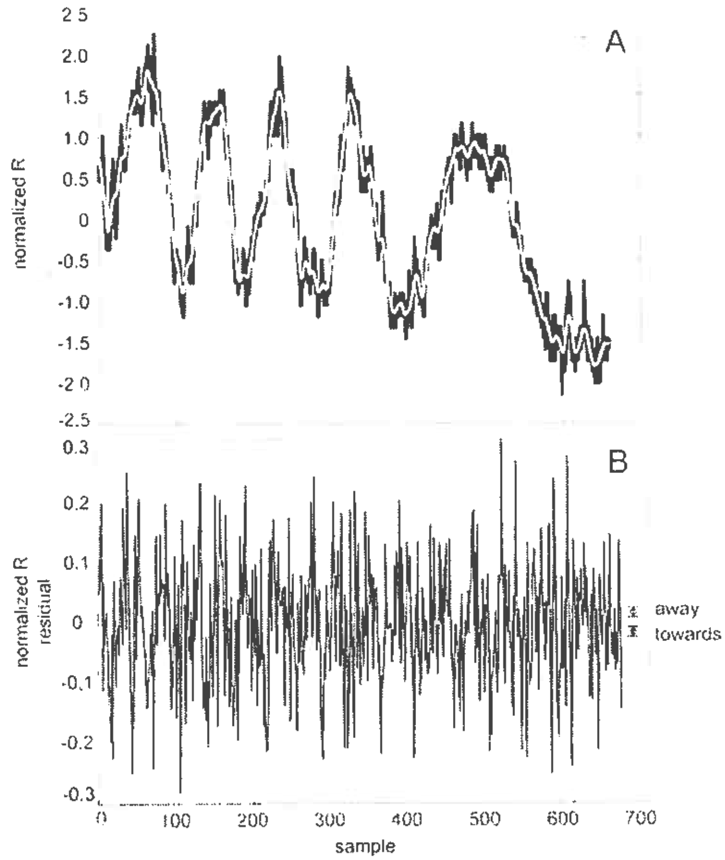

Figure 6. (A) Original R signal (in black) and 15 sample smoothed fit (in white). (B) Difference between curves in A; means and error bars on the right side indicate that the attention-towards mean residual remains significantly below the attention-away mean residual.

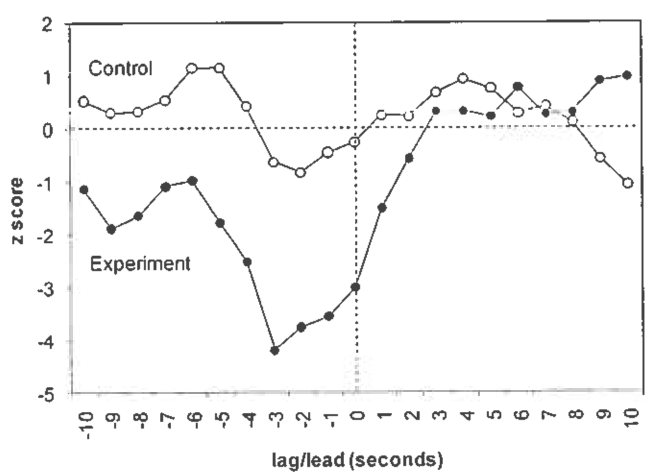

Figure 7. Lag/lead analysis for residuals. Three seconds after the condition assignments changed, at lag = -3 seconds, z = -4.2.

Experiment 2

This study was conducted as an attempt to replicate the results of the first experiment. Participants' comments from the first experiment suggested that the attention focusing task might be easier to perform with audio performance feedback to allow the experiment to be performed with eyes closed. Some also reported that the 15-second periods used in the pilot test were too short to fully reorient their attention, so the condition epochs in this study were increased to 30 seconds.

Method

Procedure

The hardware from the first experiment was used in this study along with a duplicate optical system for sessions that took place at a Zen Buddhist temple, where it was convenient to recruit meditators. Lack of environmental shielding and uncertain power line stability at the remote temple site suggest caution when interpreting results of those data.

To provide the audio feedback, the software program was revised so that during attention-away periods a continuous meditative drone sound was played, and during attention-towards periods a MIDI-synthesized tone dynamically changed pitch to reflect the real-time value of R. Participants were asked to relax when the drone tone was playing, and to intentionally decrease the pitch of the tone when that was playing. As in the first experiment, instructions for the attention-towards epochs began with a computer-synthesized voice announcing, "Please influence the beam now," and for attention-away epochs announcing, "You may now relax."

Results

A minimum of 30 sessions were planned. The test resulted in 31 sessions contributed by 19 participants. In the IONS laboratory 3 meditators contributed 11 sessions and 4 non-meditators contributed 7 sessions. In a temple in Southern California, 12 Zen Buddhist meditators contributed a total of 13 sessions. The latter tests were supervised by one of the authors (PW) using a second double-slit apparatus. Three 31-session control sessions were later conducted in the IONS lab using the original double-slit apparatus.

Table 2 summarizes the results. To perform the control tests the condition assignments used in the actual experiment were used along with newly generated R data collected without human observers present. This procedure was performed three times, each time using a new set of calibration data.

	Number	*es*	*z* lag 0	*p* lag 0	*z* lag -2	*p* lag -2
All sessions	31	-0.25	-1.39	0.08	-1.24	0.11
Meditators	11	-0.62	-2.04	0.02	-2.01	0.02
Non-meditators	7	-0.19	-0.49	0.31	-0.34	0.37
Zen Buddhist test	13	-0.01	-0.05	0.48	0.03	0.51
Controls 1	31	0.08	0.44	0.67	0.37	0.64
Controls 2	31	0.15	0.83	0.80	0.77	0.78
Controls 3	31	0.16	0.91	0.82	0.77	0.78

Table 2. Summary of results from Experiment 2.

This study again provided modest evidence in favor of **H1**. **H2** was not supported, and **H3** was supported for meditators vs. non-meditators in the IONS lab, but not for the Zen meditators using the second double-slit device. In terms of effect size, overall the results were nearly identical to those observed in Experiment 1 (-0.25 vs. -0.26, respectively). Meditators' effect size in the IONS lab was over 3 times larger than non-meditators. Control tests indicated no artifacts that might have biased the results recorded in the IONS lab.

Experiment 3

This study explored whether the results observed in the first two experiments might have been influenced by the proximity of the human body to the double-slit apparatus. While participants were always seated about 1.5 meters from the apparatus. it is conceivable that they leaned slightly towards it, or faced it, when focusing their attention, and leaned or turned away while relaxing. If this were the case, slight changes in body heat might have influenced the operation of the laser or the camera.

Method

Procedure

To test this possibility, sessions were conducted with thermocouples placed in four locations, as shown in Figure 2 (thermocouples, model 5TC-IT-T-30-72 , Omega Engineering, Stamford, CN, USA, were monitored by Measurement Computing Corporation model USB-TC-AI, Norton, MA, USA). Thermocouple accuracy was rated at 0.5°C. Each session consisted of forty counterbalanced 30-second epochs. Sessions resulting in a differential decline in R would be selected, and then the temperature measurements in those sessions tested to see if they showed a differential effect.

Results

At least 30 sessions were planned; a total of 33 were contributed. Six meditators contributed 22 sessions and 7 non-meditators contributed 11 sessions. The 22 meditator sessions resulted in a significant decline in z. with an effect size comparable to that observed in the first experiment (-0.39 vs. -0.32, respectively). To test the possible effect of proximity of the body, 16 of the 22 meditator sessions were selected that resulted in negative z scores. This subgroup produced an overall z (lag 0) = -3.65 (i.e., from a selected group, so this is not surprising). If this robust drop in R was due to systematic fluctuations in ambient temperature, then this should have been detectable in the thermocouple data.

Results summarized in Table 3 showed no statistically significant temperature differences measured on the laser tube, on the double-slit apparatus housing, in front of the apparatus, or within a meter of the participant. This suggests that the effects observed in these experiments could not be attributed to radiant heat artifacts. Other possible physical influences, such as bioelectromagnetic fields or vibrations were not tested, although the optical system's metal shielding would have attenuated most electromagnetic influences, and vibrations would have been minimal because participants sat quietly during the experiment.

	Number	*es*	*z* lag 0	*p* lag 0	*z* lag -2	*p* lag -2
All sessions	33	-0.13	-0.72	0.24	-0.72	0.24
Meditators	22	-0.39	-1.84	0.03	-1.78	0.04
Non-meditators	11	0.50	1.66	095	1.56	0.94
Selected subset	16	-0.91	-3.65	0.0001	-3.65	0.0001
Laser temperature	16	0.17	0.67	0.50	0.67	0.75
Apparatus temperature	16	0.16	0.65	0.52	0.65	0.74
Ambient temp near apparatus	16	0.15	0.61	0.54	0.65	0.74
Ambient temp near participant	16	0.19	0.76	0.45	0.79	0.79

Table 3. Summary of results from Experiment 3.

Experiment 4

If unobserved quantum events remain in an indefinite state until they are observed, then this implies that the crucial factor in the collapse of the wavefunction is when observation takes place, and not when the event is generated.[24] To test this idea, a retrocausal version of the experiment was conducted. This experiment also provided a more rigorous way to test the effect of participants' proximity to the optical system, because data in this study were recorded with the apparatus secured inside the electromagnetically shielded chamber by itself, with no one in the laboratory.

Method

Procedure

Fifty sessions with 30-second counterbalanced epochs were recorded in the IONS laboratory in April 2009. No one was present during the recording process and the data were unobserved. In June 2009 participants were asked to view a strip-chart moving graph, which unbeknownst to them was playing back the pre-recorded data. They were informed about the nature of the experiment and invited to make the graph go as low as possible when the computer gave them the instruction to "interfere with the beam," and to relax when instructed to "now please relax." The design element that made this a retrocausal rather than a real-time experiment was that the attention condition assignments were generated *during the observation phase in June*, i.e. three months after the data were generated.

Twenty-two people attending a conference in Tucson, AZ were recruited by convenience and run in this experiment in an office at the conference hotel.[25] They were each given a questionnaire asking about their meditation experience and belief in mind-matter interaction phenomena, and then they ran the experiment. After these 22 people completed their sessions, 22 of the remaining unobserved datafiles were subjected to the same analysis as a control. Individual samples in the control dataset were not observed at any time.

Results

Of the 22 participants, 10 indicated that they had a regular meditation practice; the remaining 12 were classified as non-meditators. As shown in Table 4, the meditator subgroup supported **H4** with an effect size *es* = -0.80. The other effect sizes were the virtually identical to those observed in Experiment 3. This study also supported **H2**, showing slightly more negative results at lag–2 for all sessions and for meditators.

	Number	*es*	z lag 0	*p* lag 0	z lag -2	*p* lag - 2
All sessions	22	-0.13	-0.59	0.28	-0.82	0.21
Meditators	10	-0.80	-2.53	0.006	-2.61	0.005
Non-meditators	12	0.50	1.74	0.96	1.51	0.93
Control	22	-0.13	-0.62	0.27	-0.61	0.27

Table 4. Summary results from Experiment 4.

Experiments 1 - 4 Combined

Data pooled across all 121 sessions recorded in the first four experiments comprised a total of 135, 336 *R* samples, collected one per second. Of those sessions, 67 were contributed by meditators, 41 by non-mediators, and 13 by Zen Buddhist meditators using a second double-slit apparatus in a remote location. A total of 149 control sessions were also conducted; combined the control database consisted of 175,207 *R* samples.

H1 predicted that z at the onset of the attention instructions would be negative and **H2** predicted that z would become more negative when lagged a few seconds. These were confirmed with all data and with the meditator subgroup, as shown in Figure 8 and Table 5. **H3** predicted that meditators would perform better than non-meditators. This was strongly confirmed. And as predicted by **H4**, an apparent retrocausal effect was also possible to observe. Figure 9 compares effect sizes obtained in each of the four experiments and for all data combined in experimental and control sessions. The significant meditator vs. non-meditator comparison, and the non-significant control results, argue against procedural and physical artifacts as explanations for these results.

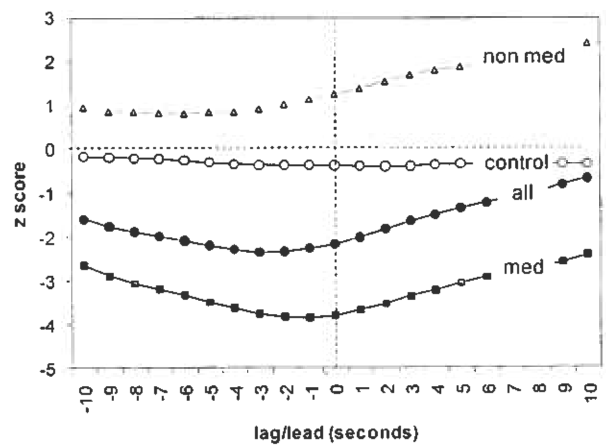

Figure 8. Combined results (weighted Stouffer Z) from 121 experimental sessions and 149 control sessions.

	Number	es	z lag 0	p lag 0	z lag -2	p lag -2
All sessions	121	-0.20	-2.17	0.015	-2.34	0.0097
Meditators	67	-0.46	-3.80	0.00007	-3.82	0.00007
Non-meditators	41	0.19	1.25	0.89	1.01	0.84
Control	149	-0.03	-0.39	0.35	-0.38	0.35

Table 5. Results combined results across sessions in Experiments 1 - 4.

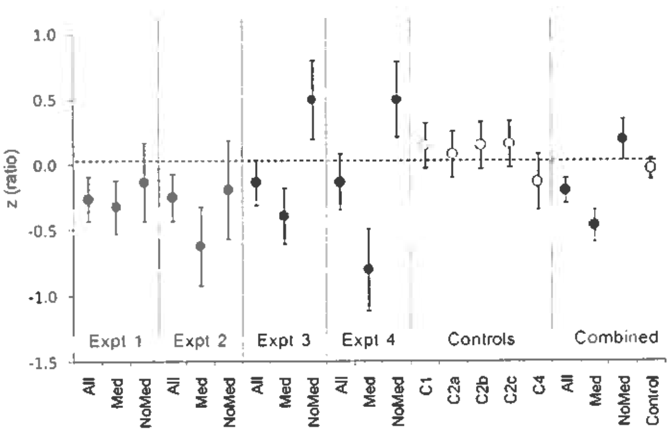

Figure 9. Comparison of effect sizes for the first four experiments and controls. The meditator effect size in Experiment 2 does not include the Zen meditators, as that portion of the study used a second double-slit apparatus and was conducted in a remote location.

Experiment 5

The study specified a preplanned series of 50 sessions, it explored the use of an electrocortical correlate of attention. and it introduced a new means of collecting and analyzing the interference data.

Method

Apparatus

The software for this study was written in Matlab 2009b (Mathworks, Natick, MA). This made the data collection process more efficient than the software used in the initial experiments, and it enabled the full interference patterns to be captured and stored at 20 camera frames per second. For exploratory purposes the study also included a wireless electroencephalograph (EEG) system to record a single channel of EEG data at 512 samples per second (Mindset, NeuroSky, San Jose, CA). The Mindset EEG device is primarily used as an inexpensive brain-computer interface: it was adapted for our purposes by enhancing its electrode system to provide improved contact with the skin, and by positioning the sensor to a left occipital site.[26] That site was selected to avoid frontal muscle artifacts. The measurement of interest was an electrocortical correlate of focused attention: alpha band event-related desynchronization (ERD, "alpha" referring to the 8 – 12 Hz brainwave rhythm).[27] The idea was to explore whether this objective measure of shifts in attention would correlate with changes in the interference pattern.

Procedure

The counterbalancing scheme used in this study alternated between attention-towards and attention-away epochs, each lasting for 20 seconds and repeated 20 times for a total of 40 alternating epochs. Each session began after collecting between 20 and 100 seconds of baseline data.

To ensure that each participant understood the nature of the task, prior to each session the 5 minute animation of the double-slit experiment was shown, followed by a discussion of the task using an illustration of the apparatus used in the actual experiment. During the session, audio feedback was provided in attention-towards epochs by associating the playback volume of a Sanskrit kirtan chant to the decline in the spectral ratio value R. To do this, the average R recorded during the last 5 seconds of the previous attention-away epoch was determined, and then the real-time R was compared to that value. To avoid sudden jumps in volume. the volume adjustment value was based on changes in R over three seconds. The lower the real-time R, the louder the music became. and vice versa. During attention-away periods. the kirtan song played at a continuous, low-level volume and it was not linked to variations in R. The attention assignments were announced via prerecorded audio files as "Now please focus on the beam," or "Now please relax."

R values were analyzed similarly to those in the initial four experiments, resulting in a z score which was predicted to be negative. In addition, the average trough height in each interference pattern was determined because hypothesis **H1** predicted that the troughs would rise as the destructive interference declined. In addition, if the troughs increased then the peaks were expected to decrease, assuming a constant level of illumination intensity, thus the average peaks were also determined.

Analyses

As noted earlier, interference pattern intensity was recorded on a 3000 pixel line camera. Values recorded before pixel 600 and after 2400 overlapped (see Figure 10), so only trough and peak heights located between pixels 600 and 2400 were identified. The average trough height was then determined for each interference pattern frame, and the differences in average troughs between the two attention conditions were evaluated using a permutation technique similar to that used to assess changes in R. The same process was used to evaluate differential changes in the peaks.

To assess the proposed correlation between the ERD measurement and the movement of the troughs in a given session, for each second of recorded EEG data the alpha power was summed (8 – 12 Hz), and then the average trough value for the same second was determined. All test sessions resulting in a significant decline in alpha power (i.e., $z < -2$) in the attention-towards vs. attention-away conditions were determined, and then all alpha power and trough measurements across those sessions were accumulated. Finally, the Pearson correlation between the resulting two arrays was calculated.

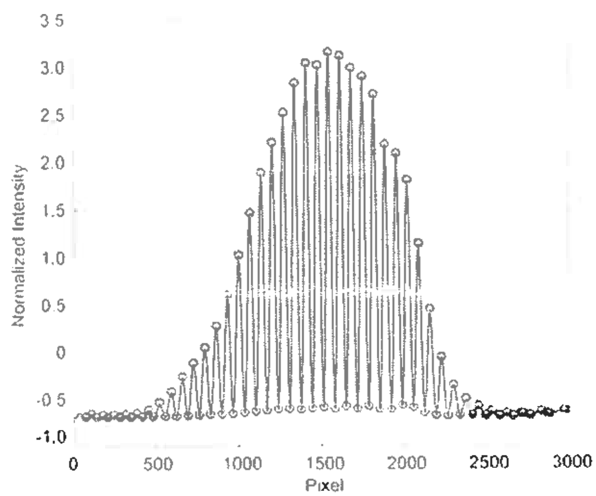

Figure 10. Interference pattern with peaks and troughs identified. The average height of the troughs and average height of the peaks between pixels 600 and 2400 were the measurements of interest. Outside that range the peaks and troughs tended to overlap and could not be clearly distinguished. Differences in the average trough and average peak in the two attention conditions were evaluated using a permutation technique similar to that used for the spectral ratio R.

Hypotheses

H1 predicted a drop in the spectral ratio R, a rise in average trough height and a drop in average peak height. **H3** predicted that well defined shifts in attention would result in clearer changes in the interference pattern. In this study, an additional **H5** predicted that the correlation between the alpha band spectral power calculated per second, and average height of the trough calculated per second, would be *negative*, because as attention increases alpha power should drop and the troughs should rise.

Results

Thirty-one people contributed 51 sessions. Only the first 50 sessions, consisting of 858,000 frames of interference pattern data, are considered here. All data contributed beyond the pre-planned number of sessions in this and the next experiment are reported separately later. Fifty control sessions were also conducted. Figure 11 and Table 6 indicate that **H1** was supported with a significant drop in *R*, a significant rise in the troughs, and a significant drop in the peaks. The effect sizes were in alignment with the meditator effect sizes observed in the first four experiments.

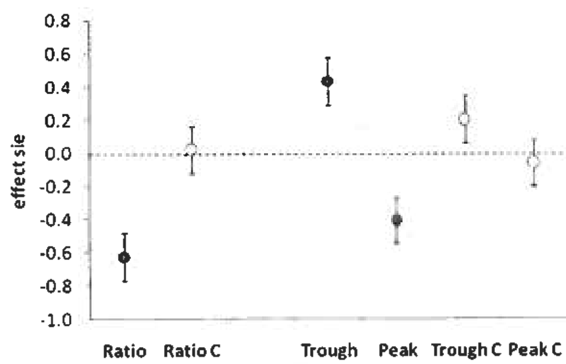

Figure 11. Effect sizes and one standard error bars for spectral ratio, average troughs and average peaks, for experimental and control data in Experiment 5.

	Number	*es*	*z*
Ratio	50	-0.63	-4.48
Ratio C	50	0.02	0.13
Trough	50	0.43	3.03
Peak	50	-0.41	-2.87
Trough C	50	0.20	1.42
Peak C	50	-0.06	-0.41

Table 6. Summary of Experiment 5 results.

Because of the strong decline observed in *R*, one may ask whether the alternating towards vs. away counterbalancing scheme, combined with a positive trend in *R* values, might have generated an artifact. That is, if *R* increased on average over the course of a session, then the comparison [mean R(towards)] – [mean R(away)] would invariably produce negative values, apparently in support of the hypothesis but actually just a consequence of the positive trend.

To test this possibility, the array of R values recorded in each session was detrended, i.e. the best fit linear trend was subtracted from the original data.[28] Then the residual from each session was reanalyzed and the z scores associated with the original data were compared to the same scores from the detrended data. The same process was performed for the control runs. If the original experimental results were due to systematic positive drifts in R, then there should be no relationship between the two sets of z scores. However, the result was a strong positive correlation both for the experimental ($r = 0.83$, $p = 7 \times 10^{-14}$, see Figure 12) and the control data ($r = 0.81$, $p = 6 \times 10^{-13}$), suggesting that the original results were not due to positive linear drifts. This outcome is similar to analysis of the nonlinear residuals in Experiment 1, suggesting that the results of these experiments are not due to mundane drifts in the data.

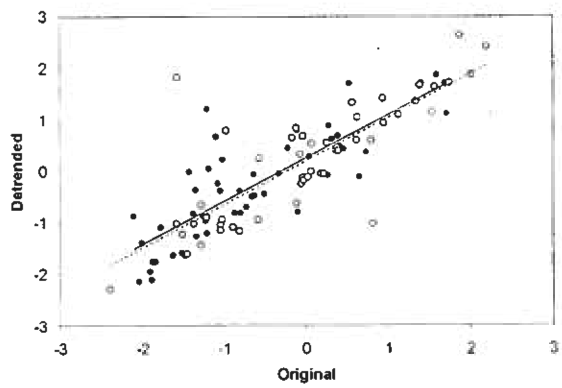

Figure 12. Solid line shows correlation between original and detrended experimental data (black dots); dashed line shows the same for control data (white dots).

For the EEG analysis, there was clear evidence for ERD in alpha power associated with shifts in attention between the two assigned conditions. Figure 13 indicates a strong drop in EEG spectral power in the lower frequencies, with a particularly strong drop within the alpha band (8 – 12 Hz), confirming the expectation that ERD could be used as an indicator of shifts in attention.

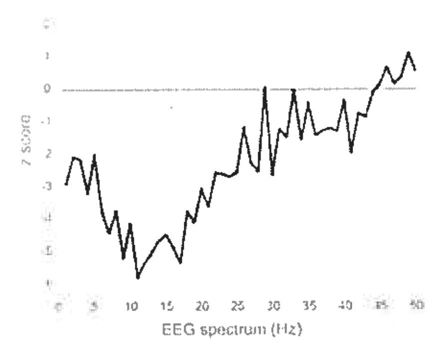

Figure 13. Drop in EEG frequency around alpha band (8 – 12 Hz) when comparing attention towards vs. away.

We then determined the statistically clearest ERD effects by selecting individual sessions where declines in alpha power between the attention-towards vs. attention-away conditions exceeded two standard errors. Four such sessions were identified. Then we calculated the correlation between all EEG alpha values recorded per second during those sessions vs. the average double-slit trough and peak values recorded per second. The result, based on a combined 3,189 seconds of data, supported **H5** with small but statistically significant correlations: r(trough) = -0.042 ($p = 0.02$), and r(peak) = 0.071 ($p = 0.0001$).

Experiment 6

This experiment investigated correlations between personality factors and beliefs in relation to decreases of the spectral ratio R and increases in the troughs and peaks. A series of 50 sessions was pre-planned with 50 different participants selected to represent a broad range of personality, meditation experience and beliefs.

Method

Procedure

Participants filled out a questionnaire asking about belief in ESP, years of meditation or other attention training experience, and a 34-item Tellegen Absorption Scale, a questionnaire that measures the degree to which one normally becomes immersed into a task while focusing.[29] The question about belief ESP was used because experiments conducted since the 1940s have shown that openness to the possibility of psychic phenomena is a reliable predictor of performance in these tasks.[30] In an attempt to create a more uniform introduction to the task, the instructions for the experiment were pre-scripted and read aloud to each participant prior to each session:

> Thank you for volunteering for this experiment in mind-matter interaction. We are testing the effects of your mental attention on instruments that are inside the box [double slit system]. You will be asked to hold the intention that you are able to affect the instruments inside the box simply by bringing your focused attention towards it. Inside the box are a laser, a metal slide with two tiny slits, and a sensitive camera. It's not important that you understand the exact workings of this system, just that your objective is to mentally connect with it.
>
> Some people do this by imagining that they're not separate from the box. Or by holding a feeling of pleasant emotions, like when you're with family and close friends. Or out in nature, or through a focused meditative practice. You'll hear music running along with the experiment. The volume of the music varies according to the degree you are able to mentally affect the box when you're asked to "bring your attention to the box." The louder the music, the greater the effect. You want the music to be as loud as possible. If you don't hear any music, you may want to adjust your focusing strategy. This is basically like a biofeedback system.
>
> When you're asked to "withdraw your attention from the box," the music will continue, but at a fixed, low volume level. The experiment consists of 40 trials, each of 20-30 seconds in duration. In twenty of these trials you'll bring your focus to the box. During the other twenty trials you'll withdraw your attention from the box and solve some simple math problems we'll give you. The purpose of the math problems is to help you withdraw your attention from the box. The frame of mind that seems to work best in this type of experiment is that of relaxed or subtle focus. It is best not to "try too hard". Now we're ready to start the experiment. We'll begin with a short demonstration of how this works.

For the last 25 sessions, two lines of the instructions were revised because many participants were confused by the suggestion to "mentally connect with" the double-slit system, and because the math problem task proved to be too distracting. The revised lines read:

> It's not important that you understand the exact workings of this system, just that your objective is to mentally connect with it *and imagine that you are closing off or blocking one of the two slits.*
>
> During the other twenty trials you'll withdraw your attention from the box ~~and solve some simple math problems we'll give you~~.

To shorten the time required to conduct a session, we did not show the video animation of the double-slit experiment. Also, to prevent participants from anticipating the beginning and end of each epoch, varying length epochs were used. Each of the 40 successive epochs ranged randomly from 20 to 30 seconds. Performance feedback again employed the volume of a kirtan chant, but this time the volume was linked to the height of a trough in the interference pattern, rather than to the spectral ratio, such that the higher the trough, the louder the music. During attention away epochs the music remained at a low, fixed volume level. Finally, each session began and ended with a 4 minute silent period, during which interference data continued to be collected.

Hypothesis

H1 predicted that *R* would drop, the average trough would rise, and the average peak would drop. **H2** predicted that the correlations between *R* vs. participants' belief in psychic phenomena, their years of meditative experience, and their capacity for absorption, would be negative, and the same correlation with trough height would be positive.

Results

50 participants contributed a total of 1.5 million frames of interference data. Half of the sessions were run at a hotel where a conference was taking place and where it was convenient to recruit participants; the other half were run in the IONS laboratory. Both the original and the secondary double-slit apparatus were used. Effect sizes shown in Figure 14 are similar to those observed in Experiment 5 for the spectral ratio *R*. The trough and peak results were in alignment with expectations, although the control trough and peak effect sizes showed similar trends, suggesting caution in interpreting those results. Figure 15 shows correlations between *R* and trough height against the three personality factors of interest. **H2** was supported for *R* for the factor of belief in ESP for *R* ($p = 0.03$) and absorption ($p = 0.02$), and suggestively for trough height for belief in ESP ($p = 0.07$).

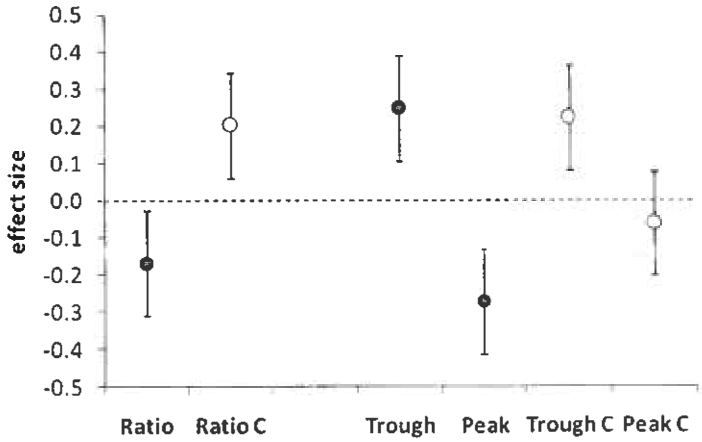

Figure 14. Effect sizes for spectral ratio, troughs and peaks in Experiment 6.

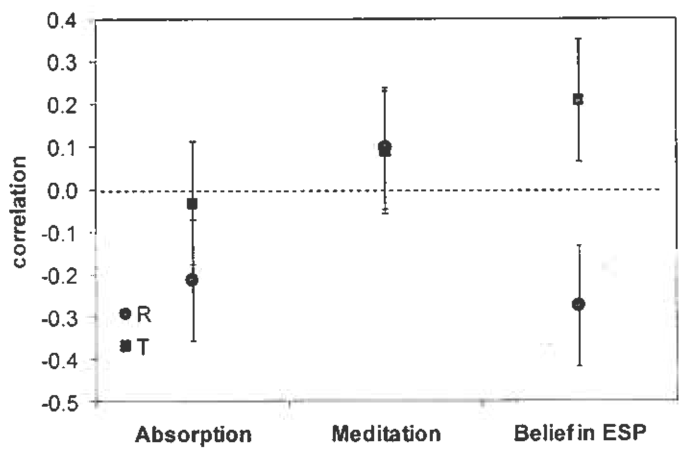

Figure 15. Correlations between *R* and change in interference pattern troughs (T) with the factors of absorption, meditation experience, and belief in ESP.

Figure 16 shows a lag/lead analysis of *R* for the 100 sessions collected in Experiments 5 and 6; Figure 17 shows the same for the average trough and peak heights. Neither shows a clear lag effect. This may be because unlike *R* in the initial four experiments, which was smoothed over 8 successive samples (1.6 seconds), in these two studies *R* was not smoothed.

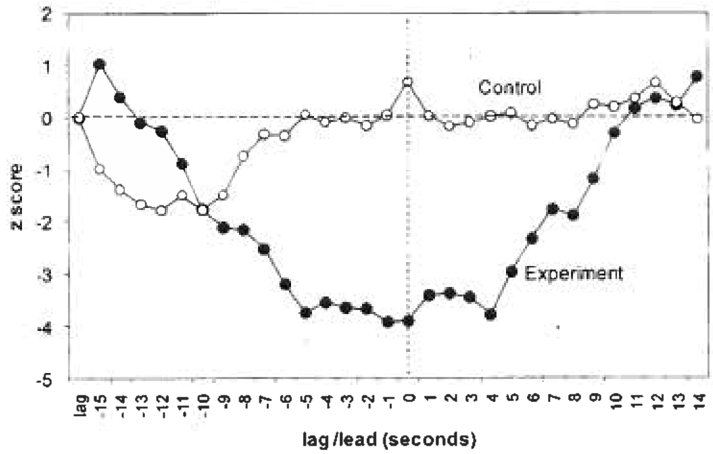

Figure 16. Lag/lead analysis for all experimental and control spectral ratio data for the 100 sessions recorded in Experiments 5 and 6.

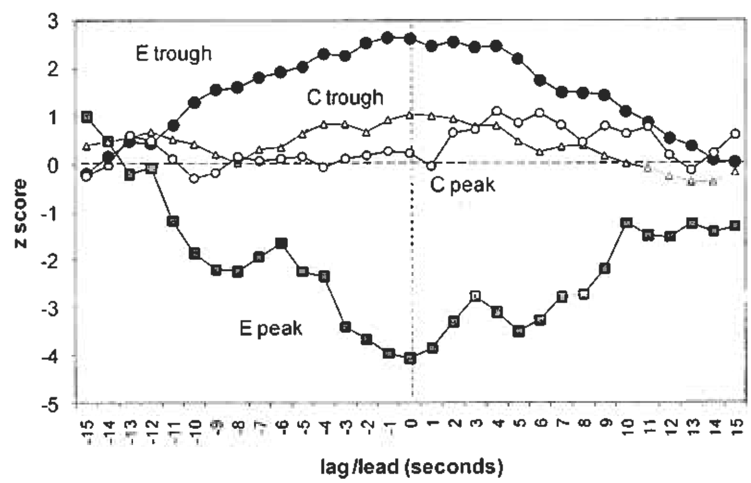

Figure 17. Lag/lead analysis for all experimental and control trough and peak data for the 100 sessions recorded in Experiments 5 and 6.

Discussion

> The doctrine that the world is made up of objects whose existence is independent of human consciousness turns out to be in conflict with quantum mechanics and with facts established by experiment. – Bernard d'Espagnat[31]

In a colloquial sense, the present experiments tested whether photons can sense when they're being stared at. The results of six experiments led to a combined 4.4 sigma effect in the predicted direction ($z = -4.4$, $p = 6 \times 10^{-6}$), suggesting that photons are indeed shy, at least when their behavior is considered in large statistical ensembles.

The control sessions provided no evidence of software, hardware or analytical artifacts that might have been responsible for these effects (cumulative z = 0.43, p = 0.67). The possibility that heat generated by the body might have caused an artifact was tested in Experiment 3 by monitoring temperature on and around the optical system, and this was tested more rigorously by collecting data without anyone present in Experiment 4. Neither study identified obvious biases that might have favored the hypothesis. That the effect might be due to systematic drifts in the signal was addressed through the use of (a) a counterbalanced protocol, which provided a built-in differential control, (b) randomized permutation analyses, which took into effect non-normal distributions and autocorrelations, and (c) examination of both linear and nonlinear residuals of the raw data. Evidence for a genuine effect withstood those analyses.

Figure 18 summarizes the *R* effect sizes for all 250 experimental and 250 control sessions. Figure 19 shows a cumulative z score for the same data, and Figure 20 shows a similar analysis for the meditator vs. non-meditator sessions. The experimental total includes 29 sessions run in the last two experiments which were not part of the preplanned design (labeled "extra" in the figure). We see that the average effect size per session over the first four experiments was about *es* = -0.20. A power analysis based on that effect size would predict a 63% chance to achieve an outcome at p = 0.05 (one-tailed) or better across the 100 sessions. The results observed in Experiments 5 and 6 exceeded this prediction, but only because of the stronger effect size observed in Experiment 5. That result may have reflected our effort to select people with meditative experience, or (unlike Experiments 4 and 6) because all of those sessions were conducted in the controlled laboratory environment, or because the use of an EEG in that study reminded the participants that their shifts in attention were being recorded, or all of these factors.

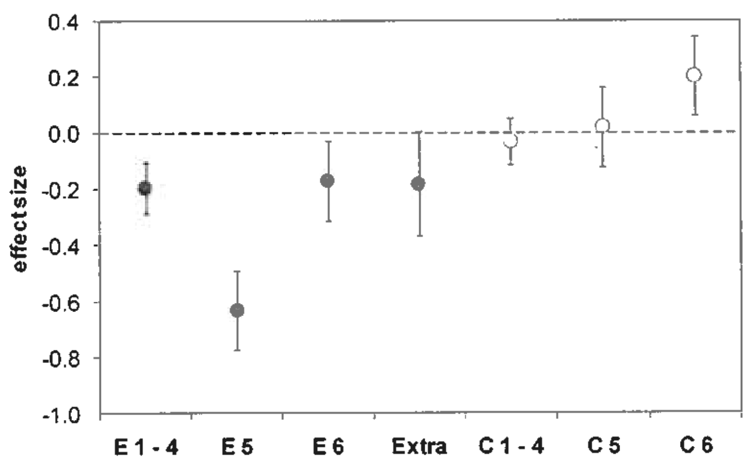

Figure 18. Spectral ratio *R* effect sizes with one standard error bars in all experiment and control tests.

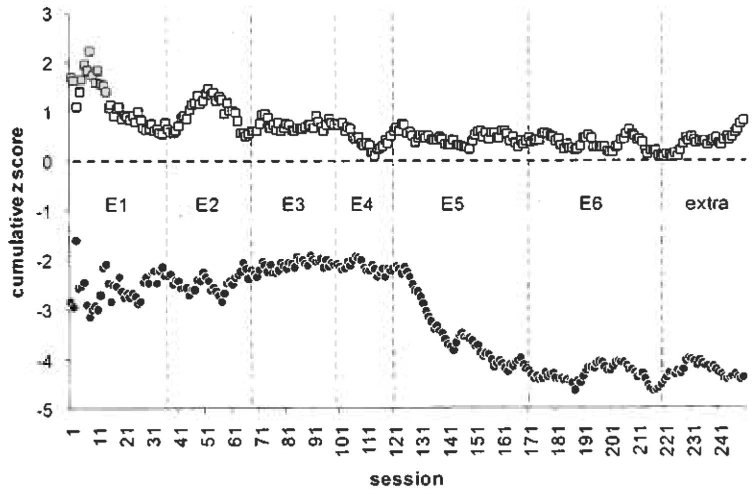

Figure 19. Cumulative z score for all 250 experimental and control sessions.

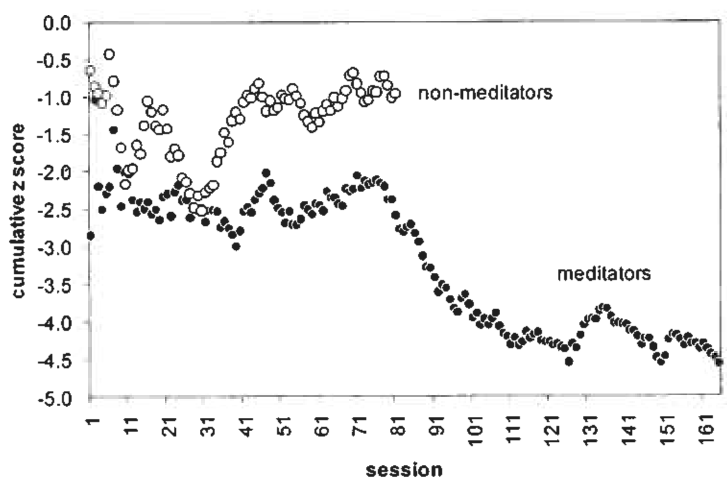

Figure 20. Cumulative z score for meditators and non-meditators in the six experiments.

Another factor possibly responsible for variations in performance from one session to the next is the Earth's geomagnetic field (GMF). This has been shown to be a significant component of the variance in many areas of human performance, from stock market behavior[32], to airplane crashes[33] and suicides[34], to variations in cardiac health,[35] and of special relevance to the present studies, to higher incidents of spontaneous reports of paranormal experiences and to enhanced performance in laboratory ESP tasks.[36-38] To test whether this factor might have influenced performance in the present experiments, the GMF Ap index was retrieved for the day of each session,[39] then those days were sorted according to magnitude of Ap. The prediction was that during days of quiet GMF, performance would increase as compared to days with noisier GMF.

with performance in the present tasks indicated by a decrease in *R*. Figure 21shows the results for subsets of the data, where each subset examined the combined *z* score for sessions conducted on the *N* quietest and *N* stormiest days, with *N* representing the contrast of interest. E.g., a contrast of say, $N = 7$ refers to the 7 days when sessions took place with the largest Ap index vs. the 7 days with the smallest Ap index, and then for the combined session *z* scores obtained on those days. The figure indicates that for high contrasts there was a strong difference in performance as predicted, with better results on low Ap days than on high Ap days. E.g., for a 7 day contrast the mean natural log of the quietest GMF days resulted in Ap = 0.49, and the session *z* combined across those 7 days = -2.3. The 7 day mean for the noisiest GMF days resulted in ln(Ap) = 3.30, and the combined z = 1.97. The difference between those high and low days was z = -3.0). This difference was maintained regardless of the extremity of the contrast, suggesting that this performance difference was genuinely modulated by GMF flux.

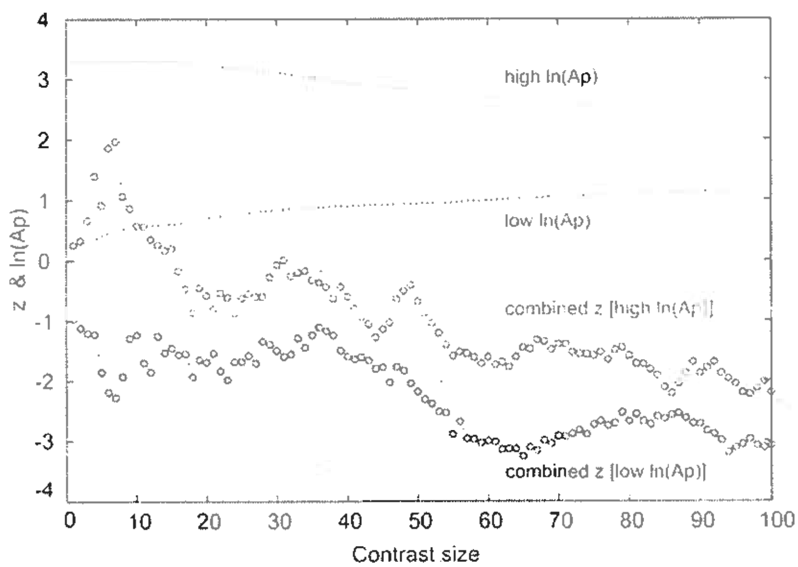

Figure 21. Examination of geomagnetic field influence on session performance across the six experiments. Contrasts of 1 to 100 are shown. A contrast size of say, 7, means the average of the 7 largest ln(Ap) values as indicated by a point on the upper dashed line, and the combined z score for sessions run on those dates as shown on the red dotted line. Likewise, it shows the 7 smallest ln(Ap) values in the bottom dashed line and the combined z score for those sessions in the blue dotted line.

These studies in context

Because it is central to interpretations of quantum mechanics, the physics literature abounds with philosophical and theoretical discussions about the measurement problem. One might expect to find a correspondingly large experimental database studying the role of consciousness in the measurement process, but this is not the case. The abundance of discussion and simultaneous scarcity of experimentation is not a mystery. That consciousness directly perturbs the physical world is associated more closely with horror movies and relics of medieval magic than it is with sober science. As a result, it is safer for one's scientific career to simply avoid broaching touchy topics.

But this is not to say the scholarly literature is completely silent. A century-long, directly relevant literature can be found in the controversial domain of (the poorly named) parapsychology. Here we find over a thousand, peer-reviewed empirical studies reporting (1) experiments testing the effects of intention on the statistical behavior of random events derived from quantum fluctuations,[40-41] (2) studies involving macroscopic random systems such as tossed dice and human physiology as the targets of intentional influence, [42-44] (3) experiments involving sequential observation to see whether a second observer could detect if a quantum event had been observed by a first observer, or if time-delayed observation would show similar effects,[45-48] and (4) experiments investigating conscious influence on nonliving systems ranging from molecular bonding in water to photons in interferometers.[49]

Much of this literature is reported in specialty journals, but given the controversial nature of the topic it is worth mentioning that some of it has also appeared in better known journals including *Science*,[50] *Nature*,[51] *Proceedings of the IEEE*[52], *Neuroscience Letters*[45], *Psychological Bulletin*,[53-54] *British Journal of Psychology*[43], and others. Cumulatively, these experiments suggest that consciousness affects the behavior of a wide range of physical systems. The observed effects tend to be small in absolute magnitude and they are not trivially easy to repeat on demand, so persistent doubt is understandable. However, high variance and replication difficulties should not come as a surprise because an essential component in all of these studies is focused attention. Like any form of human performance, the ability to focus one's attention varies substantially not just from day to day, but also within the day. Attention is influenced by numerous factors, including circadian cycle,[55-56] when one last dined and what was consumed,[57] distractions competing for one's attention, interactions between personal beliefs and the nature of the task,[58] the state of the geomagnetic field, and so on. These factors conspire to make the mind side of a postulated mind-matter interaction far more difficult to control than the matter side.

As a result, if one is prepared to take seriously the proposition that quantum objects are not independent of human consciousness, then an experiment testing this proposition cannot be regarded as a conventional physics experiment, nor as a conventional psychology experiment. The former tends to ignore subjectivity and the latter tends to ignore objectivity, neither of which is satisfactory. In attempting to accommodate both sides of the mind-matter relationship with equal care, we designed a system to create and store interference fringes that were as sharp as possible, but we also cultivated a comfortable test setting, took care to ensure that participants understood the nature of the task, selected people practiced in focusing their attention, and encouraged participants' sense of openness to the idea of extended forms of consciousness. The better results observed with the meditators suggests that in spite of unavoidable variations in human performance, it may be possible in future studies to identify those aspects of attention that are most important in producing the hypothesized effect.

It should also be noted that some meditation styles, such as mantra repetition, concentrate attention, while others, such as mindfulness meditation, expand attention. No attempt was made in these studies to assess differences among the reported meditation practices, or to independently measure participants' capacity for sustaining focused attention. But it is not unreasonable to expect that different meditative styles might well lead to different outcomes. Quantifying focused attention methods and abilities, as well as delving further into brain correlates, would be useful directions to pursue in future studies.

Acknowledgements

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