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Consciousness and the double-slit interference pattern: Six experiments

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Abstract: A double-slit optical system was used to test the possible role of consciousness in the collapse of the quantum wavefunction. The ratio of the interference pattern's double-slit spectral power to its single-slit spectral power was predicted to decrease when attention was focused toward the double slit as compared to away from it. Each test session consisted of 40 counterbalanced attention-toward and attention-away epochs, where each epoch lasted between 15 and 30 s. Data contributed by 137 people in six experiments, involving a total of 250 test sessions, indicate that on average the spectral ratio decreased as predicted ($z=-4.36$, $p=6\times10^{-6}$). Another 250 control sessions conducted without observers present tested hardware, software, and analytical procedures for potential artifacts; none were identified ($z=0.43$, $p=0.67$). Variables including temperature, vibration, and signal drift were also tested, and no spurious influences were identified. By contrast, factors associated with consciousness, such as meditation experience, electrocortical markers of focused attention, and psychological factors including openness and absorption, significantly correlated in predicted ways with perturbations in the double-slit interference pattern. The results appear to be consistent with a consciousness-related interpretation of the quantum measurement problem. © *2012 Physics Essays Publication.* [DOI: 10.4006/0836-1398-25.2.157]

Résumé: Un système optique de double fente est utilisé pour tester le rôle possible de la conscience dans la réduction du paquet d'onde en mécanique quantique. On fait l'hypothèse que l'intensité relative de la figure d'interférence produite par une double fente devrait diminuer quand le sujet focalise son attention sur la double fente. Cette intensité est estimée en calculant une mesure normalisée de la puissance spectrale à la fréquence spatiale où le phénomène d'interférence est observé. Chaque session est composée de 40 essais contrebalancés d'une durée comprise entre 15 et 30 secondes, où le sujet porte son attention soit vers soit au loin de la double fente. Les données fournies par 137 sujets, pour un total de 250 séances d'essais recueillis lors de 6 expériences, indiquent qu'en moyenne, l'intensité de la figure d'interférence diminue dans la direction escomptée ($z = -4,36$, $p = 6 \times 10^{-6}$). En outre, 250 sessions de contrôle effectuées en l'absence de tout observateur ont permis de tester la présence d'artéfacts potentiels en provenance du matériel, des logiciels et des méthodes d'analyse; aucun effet n'est observé ($z = 0,43$, $p = 0,67$). D'autres variables telles que la température, les vibrations et la dérive du signal ont également été testées, et aucune influence parasite n'a pu être identifiée. En revanche, les facteurs associés à la conscience, comme l'expérience de la méditation, les mesures électrophysiologiques de l'attention focalisée, et les facteurs psychologiques comme les mesures d'absorption et d'ouverture d'esprit sont significativement corrélés dans une direction prédictible avec les perturbations d'intensité de la figure d'interférence. Ces résultats sont en accord avec les interprétations qui lient la conscience au problème de la mesure quantique.

Key words: Quantum Measurement Problem; Consciousness; Double-Slit Experiment; Mind–Matter Interaction.

I. INTRODUCTION

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

In this opening quotation, Feynman is referring to the quantum measurement problem (QMP), and in particular to the curious effect whereby quantum objects appear to behave differently when observed than when unobserved.[2] The QMP is a problem because it violates the common-sense doctrine of *realism*, which assumes that the world at large is independent of observation. The conflict between naive realism and what the QMP implies

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forced many of the early developers of quantum theory to ponder the meaning of observation and measurement.[3,4] Some, like Pauli, Jordan, and Wigner, believed that some aspect of consciousness—referring to mindlike capacities such as awareness, attention, and intention—was fundamental in understanding the QMP.[5,6] 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.[7]

This strong view of the role of consciousness in the QMP has been endorsed by physicists ranging from d'Espagnat to von Neumann, from Stapp to Squires.[8–11] The significance of the proposition and the prominence of those who have proposed it have made the idea difficult to blithely ignore, but to many it challenges a deeply held intuition that the physical world was here, more or less in its present form, long before human consciousness evolved to observe it. As a result, many continue to resist the idea that consciousness has anything to do with the formation of physical reality.[12,13]

One approach to eliminating the observer from the QMP has been to reframe the problem by proposing that all that observation does is increase our knowledge about a measured system. Thus, according to Zeilinger,

> 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]

Another approach is to argue that decoherence theory obviates the QMP, but this proposal is not without problems.[15,16] Others have attempted to finesse the QMP by denying that there ever was a problem. According to Goldstein,

> 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.[12]

Still others have proposed that the only unambiguous way to avoid the role of the observer in physics is to deny the belief that we have free will.[17]While free will as a brain-generated illusion is the prevailing assumption in the neurosciences today,[18] that idea remains at odds with the only direct form of contact we have with reality—subjective experience—which paradoxically allows for the experience of deciding to believe that free will does not exist.

Philosophical and theoretical arguments aside, the double-slit experiment suggests a way to explore the meaning of observation in the QMP, and in particular the possible role of consciousness. It is based on two assumptions: (a) If information is gained—by any means—about a photon's path as it travels through two slits, then the interference pattern will collapse in proportion to the certainty of the knowledge gained; and (b) if some aspect of consciousness is a primordial, self-aware feature of the fabric of reality, and that property is modulated by us through capacities we know as attention and intention, then focusing attention on a double-slit system may in turn affect the interference pattern. The first assumption is well established.[19] The second, based on the idea of panpsychism, is a controversial but respectable concept within the philosophy of mind.[20]

A. Experimental background

Three earlier experiments have employed optical interferometers to investigate the possibility of what we will call the "consciousness collapse hypothesis." Two of those experiments employed a double-slit system[21] and one used a Michelson interferometer.[22] In the first study, a team at York University used a HeNe laser and double-slit apparatus to test unselected volunteers who were 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 who were experienced at attention-focusing tasks, and with a refined version of the York optical system.[21] The goal in both experiments was to shift the mean of a variable that measured the wavelike versus particlelike nature of the interference pattern. The York team reported a nonsignificant mean shift opposite to the predicted direction (although curiously, the data showed a significantly larger variance than would be expected by chance); the Princeton team reported a modestly significant mean shift in the predicted direction ($p=0.05$).

The third experiment involved a Michelson interferometer located inside a light-tight, double-steel-walled, electromagnetically shielded chamber.[22] Participants one at a time sat quietly outside the chamber and were instructed to direct their attention toward or away from one arm of the interferometer. Interference patterns were recorded once per second and the average intensity levels of those patterns were compared in 30 s counterbalanced attention-toward and attention-away epochs. At the completion of the experiment, the results were in accordance with the prediction ($p=0.002$), i.e., interference was reduced during the observation periods. This outcome was primarily due to nine sessions involving experienced meditators ($p=9.4\times10^{-6}$). The remaining nine sessions with nonmeditators did not produce effects differing from those of chance ($p=0.61$). Control runs using the same setup but with no observers present also produced chance results.

In sum, of three experiments relevant to the issue at hand, two support the consciousness collapse hypothesis to a statistically significant degree, and one does not. Given the importance of the QMP and the potential of

FIG. 1. From the left, 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 matte black and optically sealed.

this type of experiment to inform it empirically, we conducted a new series of studies 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 experiments described here, both preplanned and exploratory, were considered part of the formal 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 data-acquisition glitches.

II. EXPERIMENT 1

A. Method

1. Apparatus

A 5 mW linearly polarized HeNe laser beam (632.8 nm; model 25 LHP 151–249, CVI Melles-Griot, Albuquerque, NM, USA) was passed through a neutral density filter (i.e., a gray filter that attenuates all wavelengths equally, in this case by 90%; Rolyn Optics, Covina, CA, USA), and then through two slits etched through a metal foil slide with widths of 10 μm and a separation of 200 μm (Lenox Laser, Glen Arm, MD, USA). The resulting interference pattern was recorded by a 3000-pixel charge-coupled device line camera, which had a pixel size of 7.0 by 0.2 μm and 12-bit analog-to-digital resolution (Thorlabs Model LC1-USB, Newton, NJ, USA). The camera was located 10.4 cm from the slits. This laser was selected because it has a coherence length of more than a meter, which helped to produce sharp interference fringes. Prior to its use in this study it had been in operation for several thousand hours; this provided improved power-output stability as compared to a new laser. A duplicate optical system was also constructed with similar components, for tests conducted outside the laboratory.

The apparatus was housed inside a custom-machined aluminum housing and painted matte black inside and out (see Fig. 1). The laser and camera were allowed to warm up for a minimum of 45 min prior to test sessions. 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.

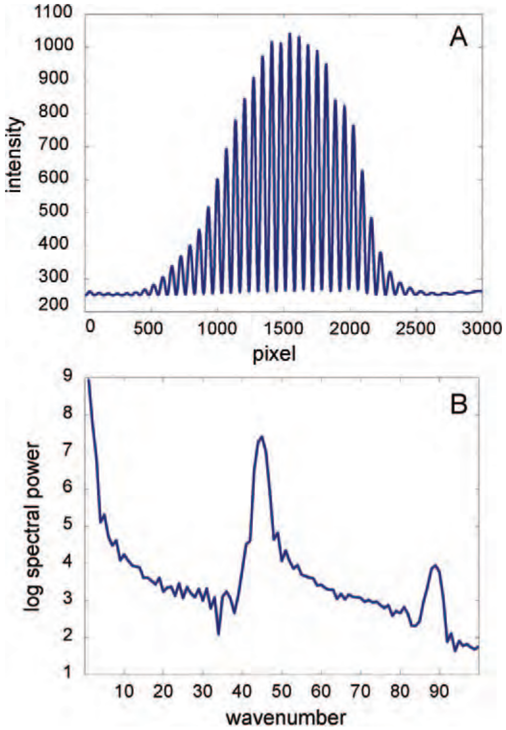

FIG. 2. (Color online) (A) Interference-pattern intensity recorded by the 3000-pixel line camera, averaged over 10,000 camera frames. (B) Log of spatial spectral power with double-slit power peaking around wavenumber 45 (equivalent to a wavelength of about 69 pixels) and single-slit power at 1. The peak around wavenumber 90 is a harmonic of the double-slit frequency.

To measure perturbations in the wavefunction, the interference pattern recorded by the line camera was analyzed with a fast Fourier transform to quantify the power associated with the two dominant spatial wavelengths: a shorter wavelength associated with the double-slit interference pattern (call this power P_D) and a longer wavelength associated with the diffraction pattern produced by each slit (P_S) (see Fig. 2). The fraction of (log) spectral power associated with the interference pattern was $D=[P_D/(P_D+P_S)]$, and that with the diffraction pattern was $S=[P_S/(P_D+P_S)]$. The ratio of these fractions, $R=D/S$, was the preplanned variable of interest.

2. Procedure

During a test session, participants were instructed by the computer to direct their attention toward the double-slit apparatus or to withdraw their attention and relax. To announce the attention-toward task, a computer-synthesized voice said, “Please influence the beam now”; for attention away, it said, “You may now relax.”

Participants were asked to direct their attention toward two tiny slits located inside a sealed black box (the double-slit optical system). It was explained that this task was purely in the “mind’s eye,” i.e., an act of imagination. To many this instruction proved to be somewhat abstract, so to assist their imagination they were shown a 5 min animation of the double-slit experiment, where a particle detector was portrayed as

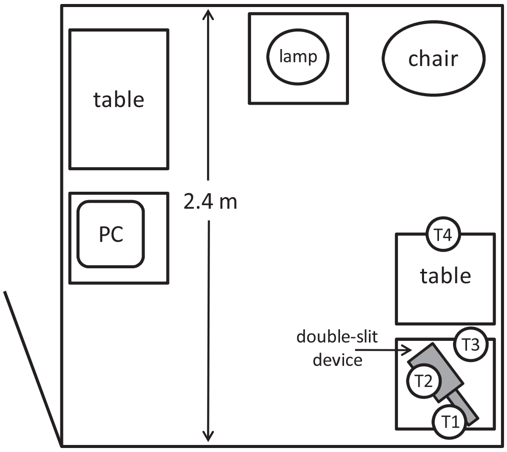

FIG. 3. Experiments were conducted inside a double-steel-walled, electromagnetically shielded chamber. The computer (PC) controlled all aspects of the experiment, including announcement of the attention-toward and attention-away instructions and acquisition of interference-pattern images from the double-slit 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).

analogous to a human eye. If the task was still unclear, it was suggested that they could try to mentally block one of the slits, or to "become one with" the optical system in a contemplative way, or to mentally push the laser beam to cause it to go through one of the two slits rather than both.

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

Participants one at a time sat quietly about 2 m from the sealed optical apparatus (see Fig. 3). They were instructed not to touch or approach the device at any time. 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, USA). Electrical-line power in the chamber was conditioned through a high-performance electromagnetic interference filter (ETS-Lindgren filter LRW-1050-S1), and to further reduce potential electromagnetic interference, the optical system and computer were powered by a battery-based uninterruptable power supply. This testing chamber in its unadorned state is a rather imposing steel cube without windows, so to make it more welcoming the walls and ceiling were covered with a tan-colored muslin fabric, antistatic carpeting was installed on the floor, and comfortable furniture was placed inside the chamber.

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.

3. Analysis

The computer calculated R five times a second and then stored and displayed the average of the last eight measurements once per 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 specified the attention-toward and attention-away conditions for each sample in R_z (call this array C) From these two arrays, the differential measure $\Delta_R=\bar{R}_{zA}-\bar{R}_{zB}$ was formed, where $\bar{R}_{zA}$ was the mean of R_z values collected during in the attention-toward condition and $\bar{R}_{zB}$ 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 took into account possible autocorrelated dependencies between successive R_z samples. To perform this analysis, (1) the original array of R_z samples was circularly shifted N steps, where N was randomly selected between 1 and the total number of samples in the array; and (2) using the new, randomly time-shifted array with the original condition array C, the differential measure Δ_R was determined (as described in the previous paragraph) and stored. Steps 1 and 2 were then repeated 5000 times. This procedure generated a distribution of possible Δ_R outcomes, differing from the original only by when each test session effectively began. The statistic used to assess Δ_{Ro} was $z=(\Delta_{Ro}-\mu_{\Delta R})/\sigma_{\Delta R}$, where the subscript o in Δ_{Ro} refers to the experimentally observed value for Δ_R, the term $\mu_{\Delta R}$ indicates the mean of the distribution of randomly time-shifted Δ_R values, and the term $\sigma_{\Delta R}$ indicates the standard deviation of that same distribution. The value z was thus a standard normal deviate, with expected mean 0 and standard deviation 1.

4. Hypothesis

The consciousness collapse hypothesis predicted that the act of focusing attention toward the double-slit would cause R recorded during attention-toward epochs to decrease as compared to during attention-away epochs. Because being able to concentrate one's attention was an important aspect of the assigned instructions, it was further predicted that participants with attention training, such as meditators, would perform better than those without such training.

B. Results

A minimum of 30 sessions were planned. Unselected participants were recruited by convenience, and 15 participants ended up contributing 35 sessions (the five

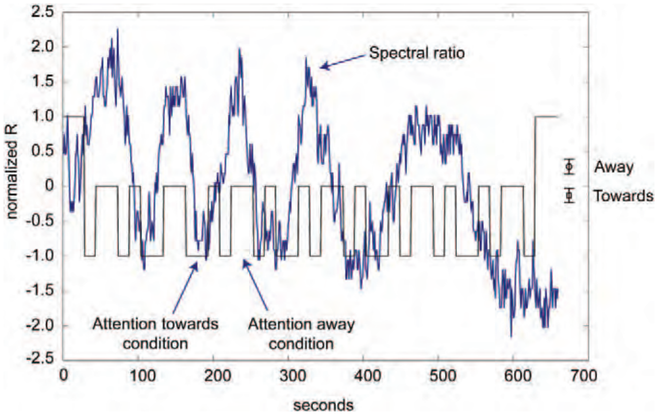

FIG. 4. (Color online) Example of the data for the normalized spectral ratio R recorded in one test session. Attention assignments are plotted for illustrative purposes as the values +1 for pre- and postsession baseline periods, 0 for attention away, and −1 for attention toward. On the right side of the graph the means for R by condition are shown, along with one standard error of the mean error bars. Normalizing the signal exaggerates its apparent variance; this signal varied from the grand mean measured over all 35 sessions by an average of 0.5%.

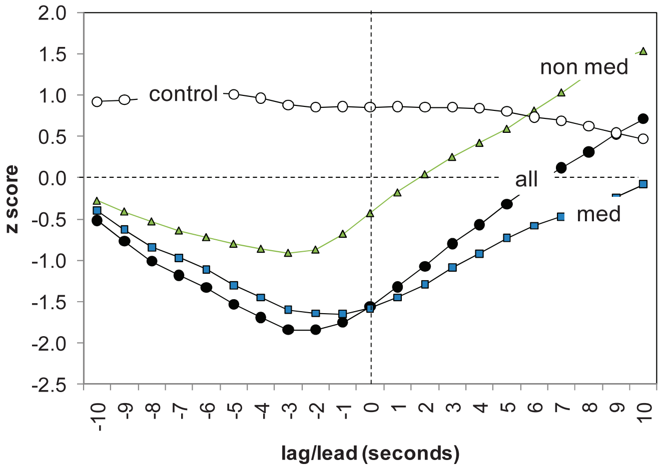

FIG. 5. (Color online) The z scores for lag/lead analysis. Zero lag refers to R synchronized with the beginning of the announcement of the attention conditions. Negative lags refer to R after changes in attention assignments, and positive lags to R before such changes.

extra sessions are included in this analysis to avoid selective reporting biases). At $15\,\text{s/epoch}\times 1\,R/\text{s}\times 40\,\text{epochs/session}$, this produced a total of 21 000 R measurements, half in the attention-toward condition and half in the attention-away. Twenty-four sessions were contributed by people who reported some meditation experience and 11 by nonmeditators. No attempt was made to distinguish among different styles of meditation or to formally assess meditation expertise. An additional 34 calibration sessions were run using the same hardware and software and with the apparatus in the same location as during experimental runs, but with the computer's speakers muted and no one present in the shielded chamber.

Across the 35 sessions the recorded R signal was fairly stable. The variation across all sessions was an average of $v=0.5\%$, where v per session was calculated as $v=[\max(R)-\min(R)]/\bar{R}$.

Figure 4 illustrates the normalized R value and the counterbalanced condition assignments for one session. As with any interferometer, some drifts and oscillations are to be expected, thus the signal variations in Fig. 4 are not as large as they may appear to be; also, the graph exaggerates the apparent variance due to the signal-normalization process. The figure also indicates the means of R in the attention-away and attention-toward conditions, along with one standard error of the mean error bars (determined using the randomized-permutation technique).

TABLE I. Summary of results from experiment 1. Effect size *es* expresses the magnitude of the effect per session, z is the outcome of comparing R between the two attention conditions, p is the one-tailed probability associated with z, "0 lag" indicates the analysis with R in exact time synchrony with the change of the attention condition, and "−2 lag" indicates the same analyses with R lagged 2 s after the change of the attention condition.

	Sessions	*es*	z 0 lag	p 0 lag	z −2 lag	p −2 lag
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
Nonmeditators	11	−0.13	−0.43	0.34	−0.87	0.19
Controls	34	0.15	0.85	0.80	0.85	0.80

Table I indicates that for experiment 1, the spectral ratio R declined modestly in accordance with the consciousness collapse hypothesis ($z=-1.56$, where z is the normalized statistic associated with Δ_R, as described in Subsection II.A.3), and a somewhat stronger effect was observed for meditators ($z=-1.58$) than for nonmeditators ($z=-0.43$). Control tests using the same equipment in the same location, but without participants present, showed a slightly positive result (i.e., opposite to the hypothesis, $z=0.15$). Table I also displays the *effect size* for each condition, where $es=z/\sqrt{N}$ and N is the number of sessions. Effect size is a convenient way to compare the magnitude of effects across different studies and subsets of studies, because it is independent of the number of sessions. From this perspective, meditators produced effects 2.5 times as large as those produced by nonmeditators ($es=-0.32$ and -0.13, respectively). The effect size for all data combined ($es=-0.26$) is comparable in absolute magnitude to experimental effects commonly observed in the behavioral and social sciences. For example, a 2003 meta-analysis of a century of social-psychology experiments, involving some 25 000 studies and 8×10^6 people,[23] found that the grand mean effect size was $es=0.21$. Effects of this magnitude are generally considered "small." Small effect sizes in the behavioral sciences are considered real phenomena,[24] but they require repeated testing to provide enough statistical power for detection.

The last two columns in Table I refer to a lag/lead analysis. This was conducted because it took the computer a few seconds to speak aloud the condition assignment and for participants to shift their mental attention; thus if the change in R was indeed related to shifts of attention, then we might expect a short lag in the response time of R. The result is illustrated in Fig. 5. The x-axis shows the effects of

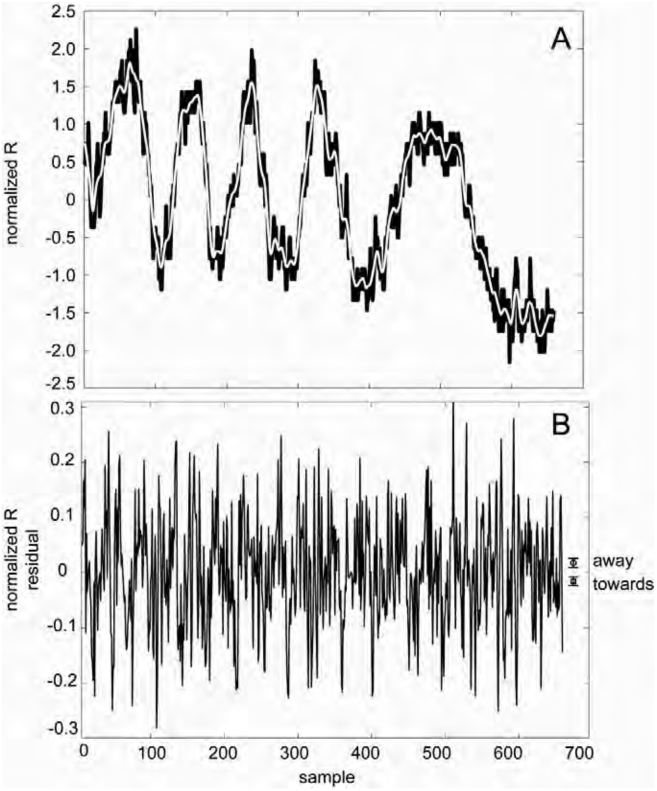

FIG. 6. (A) Original R signal (in black) and 15-sample smoothed fit (in white). (B) Difference between curves in part (A); means and error bars on the right side indicate that the attention-toward mean residual remains significantly below the attention-away mean residual.

time-lagging R with respect to the onset of the attention-condition assignments. Thus a lag of 0 refers to R recorded in synchrony with the onset of the attention assignment, a lag of -1 to the same analysis with R lagged 1 s after the condition assignments, a lag of $+1$ to R leading 1 s before the condition announcement, and so on. This analysis indicates that for all data combined, z declined when lagged a few seconds. By contrast, the control test data remained positive and relatively flat through 10 s of lag/lead analysis. The figure shows that the optimal lag length was about 2 s, so Table I and subsequent tables summarize this analysis for a lag of -2.

From the example session shown in Fig. 4, the question may arise as to whether the primary effect in this experiment might have been due to fortuitous matches between the condition assignments and slow oscillations in R. In the present case, randomly assigned counterbalanced conditions were employed to reduce the possibility of chance dependencies on such oscillations, but this was further examined by smoothing R with a 15-sample moving linear regression (1 sample/s) and then determining the difference between the original signal and the smoothed signal to create residuals (see Fig. 6). When residuals from all sessions were combined and analyzed using the permutation technique, the result remained significant at $z(\text{lag}\,0)=-2.8$, as shown in Fig. 7. Thus drifts and oscillations do not appear to be responsible for the observed results. To help maintain as transparently simple an analytical approach as possible, the normalized unfiltered signal was used in all subsequent analyses.

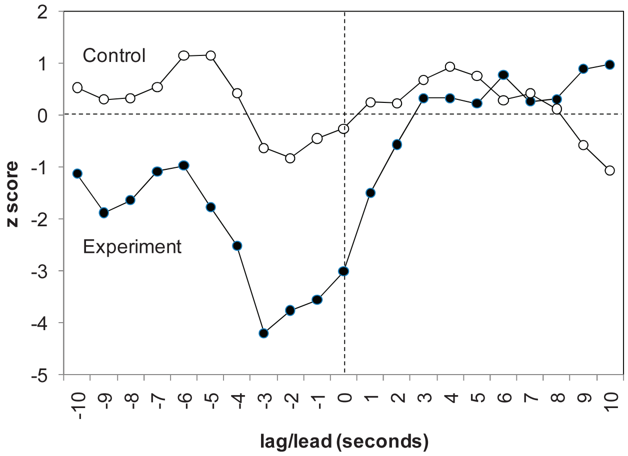

FIG. 7. (Color online) Lag/lead analysis for residuals.

III. EXPERIMENT 2

Participants' comments about the first experiment suggested that the attention-focusing task might be easier to perform with audio feedback to allow the experiment to be performed with eyes closed; in addition, a number of participants suggested that 15 s periods were too short to fully reorient their attention. Thus in this experiment an audio-feedback technique was developed and the condition-epoch lengths were increased to 30 s. Along with the original double-slit device, a duplicate system was used for some remote test sessions conducted at a Zen Buddhist temple, which was a convenient location to recruit meditators for the experiment.

A. Method

For audio feedback, during attention-away periods the computer played a soft, continuous drone tone, and during attention-toward periods it played a musical note that changed pitch to reflect the real-time value of R. Participants were instructed to direct their attention toward the double-slit device as in the initial study. If they were successful, then the double-slit spectral power was predicted to decline, and in turn the pitch of the musical note would also decline.

B. Results

A minimum of 30 sessions were planned. The test concluded after 19 participants contributed 31 sessions. In the Institute of Noetic Sciences (IONS) laboratory, three meditators contributed 11 sessions and four nonmeditators contributed 7 sessions. In the Zen Buddhist temple, 12 meditators contributed a total of 13 sessions. The latter tests were supervised by one of the present authors (Wendland), using a duplicate double-slit apparatus. Three control sessions, each consisting of 31 sessions, were later conducted in the IONS lab using the original double-slit apparatus.

Table II summarizes the results. To perform the control tests, the condition sequences assigned in the

TABLE II. Summary of results from experiment 2. (See Table I caption for explanations.)

	Number	*es*	*z* 0 lag	*p* 0 lag	*z* −2 lag	*p* −2 lag
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
Nonmeditators	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
Control 1	31	0.08	0.44	0.67	0.37	0.64
Control 2	31	0.15	0.83	0.80	0.77	0.78
Control 3	31	0.16	0.91	0.82	0.77	0.78

actual experiment were compared against new *R* data generated without human observers present. This procedure was performed three times, each time using a new set of control data.

This study provided modest evidence in favor of the hypothesis ($z=-1.39$), and in the IONS lab meditators again showed superior performance ($z=-2.04$) as compared to nonmeditators ($z=-0.49$). In terms of effect size, the overall results were nearly identical to those observed in the first experiment (−0.25 in experiment 2 vs. −0.26 in experiment 1). There was no evidence that *R* lagged the real-time condition assignments as it did in experiment 1. Control tests identified no artifacts that might have biased the results recorded in the IONS lab.

The Zen meditators using the second double-slit device failed to support the hypothesis. Two differences in that study are noteworthy because they may have introduced unforeseen variance: (a) The test sessions took place outside a controlled laboratory environment, and (b) the Zen temple was in a rural location with erratic line power. In an attempt to accommodate unpredictable "brownouts" in line power, a voltage converter was used to provide uniform power to the laser below its usual 110 V operating conditions. Both of these factors may have altered the experiment outcome in unanticipated ways, but we nevertheless include those data here for the sake of completeness.

IV. EXPERIMENT 3

Participants in sessions in the first two studies that were conducted in the laboratory were seated about 2 m from the optical system. In some cases they may have leaned toward the device or faced it more directly when focusing their attention, and leaned back or turned away while relaxing. If this occurred systematically, it might have introduced changes in radiant heat impinging on the optical system, and that in turn might have influenced the interference pattern. For example, the distance between the slits or the length of the HeNe laser tube might have expanded or contracted slightly due to temperature fluctuations. To test this possibility, a third experiment was designed to explore the effects of human body heat in proximity to the double-slit apparatus.

A. Method

Sessions were conducted with thermocouples (model 5TC-IT-T-30-72, accuracy rated at 0.5 °C; Omega Engineering, Stamford, CT, USA; monitored by a Measurement Computing Corporation analog-to-digital converter, model USB-TC-AI, Norton, MA, USA placed in four locations, as shown in Fig. 3. Each session consisted of 40 counterbalanced 30 s epochs. Individual sessions were identified that showed a marked differential decline in *R*, and then the thermocouple measurements in those sessions were compared between the two conditions to see if temperature also showed a differential effect. If it did, then what was previously observed might have been due to subtle changes in ambient temperature rather than to shifts in attention.

B. Results

A minimum of 30 sessions were planned; a total of 33 were contributed. Six meditators contributed 22 sessions and seven nonmeditators 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; see Table III). To test for possible temperature-mediated effects, all meditator sessions resulting in negative *z* scores were selected ($N=16$) to form a subset with an especially strong statistical effect.

TABLE III. Summary of results from experiment 3. (See Table I caption for explanations.)

	Number	*es*	*z* 0 lag	*p* 0 lag	*z* −2 lag	*p* −2 lag
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
Nonmeditators	11	0.50	1.66	0.95	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 IV. Summary of results from experiment 4. (See Table I caption for explanations.)

	Number	*es*	*z* 0 lag	*p* 0 lag	*z* −2 lag	*p* −2 lag
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
Nonmeditators	12	0.50	1.74	0.96	1.51	0.93
Control	22	−0.13	−0.62	0.27	−0.61	0.27

This selected subgroup produced a combined $z=-3.65$. If that decline was attributable to systematic fluctuations in ambient temperature, then this should have been detectable in the thermocouple measurements.

Results of the analysis showed no significant temperature differences measured on the laser tube ($z=0.67$), on the housing of the double-slit apparatus ($z=0.65$), in front of the apparatus ($z=0.61$), or within a meter in front of the participant ($z=0.76$; see Table III). It is interesting that all of these differential measurements were positive, indicating that on average, temperature did increase slightly on and around the double-slit system during the attention-toward condition. But the lack of statistical significance in the temperature measurements suggests that the robust decline in R observed in the 16 selected sessions was probably not driven by systematic variations in radiant heat. Other physical influences, such as human bioelectromagnetic fields and vibrations, were not explicitly tested, although the optical system's metal shielding would have attenuated higher-frequency electromagnetic influences, and vibrations would have been minimal because all participants (especially the meditators) were sitting quietly during the experiment. Nevertheless, the possibility that undetected factors associated with proximity of the human body influenced the results prompted the design of the next experiment.

V. EXPERIMENT 4

If the consciousness collapse interpretation of the QMP is valid, then this implies that the collapse occurs when observation takes place, and not when the event is generated.[25] To test this idea, a retrocausal version of the experiment was designed. This test also provided a more rigorous way to test the effect of participants' proximity to the optical system, because the data in this study were generated and recorded with the apparatus located by itself inside the electromagnetically shielded chamber, and with no one else in the laboratory.

A. Method

Fifty sessions with 30 s counterbalanced epochs were recorded in the IONS laboratory in April 2009. No one was present during the process of data generation and recording, and the data remained unobserved. In June 2009, participants were asked to view a strip-chart display, which unbeknownst to them played back prerecorded but previously unobserved data. As in the other experiments, they were invited to cause the value R to go as low as possible when the computer gave them the instruction "Interfere with the beam now," and to relax when instructed "Now, please relax." The design feature that made this a retrocausal experiment was that the attention-condition assignments were generated and assigned *during the observation phase*, which took place 3 months after the data were generated and recorded.

Twenty-two people attending a conference in Tucson, Arizona, USA, were recruited by convenience and run in this experiment in an office at the conference hotel. The participants signed an informed consent, filled out a brief questionnaire asking about their meditation experience and belief in phenomena of mind–matter interaction, and then ran the experiment. After participants completed their sessions, 22 of the remaining unobserved data files were subjected to the same analysis as a control. Individual samples in the control data sets were not observed at any time.

B. Results

Of the 22 participants, 10 indicated that they had a regular meditation practice; the remaining 12 were classified as nonmeditators. As shown in Table IV, the meditator subgroup supported the hypothesis, with an effect size of $es=-0.80$.

VI. FIRST FOUR EXPERIMENTS COMBINED

Data pooled across the 121 sessions collected in the first four experiments comprised a total of just over 135 000 R samples, one per second. Of those sessions, 67 were contributed by meditators, 41 by nonmeditators, and 13 by 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 approximately 175 000 R samples.

The principal hypothesis predicted that overall z would be negative, indicating a differential drop in the spectral ratio R during focused-attention periods relative to no-attention periods. A secondary hypothesis was that the differential drop would be stronger for meditators than for nonmeditators, and a tertiary hypothesis was that the effect would become more negative when lagged a few seconds. All of the hypotheses were confirmed, with the principal and secondary predictions confirmed to a significant degree (see Fig. 8 and Table V). Figure 9 compares effect sizes obtained in the four experiments and for all data combined.

VII. EXPERIMENT 5

The first four experiments appeared to confirm the consciousness collapse hypothesis, so a fifth study was designed both as a formal replication and as a means of exploring two new factors: (a) An electrocortical marker of attention was recorded to see whether an objective correlate of attention would be associated with declines in R, and (b) the interference-pattern peaks and troughs

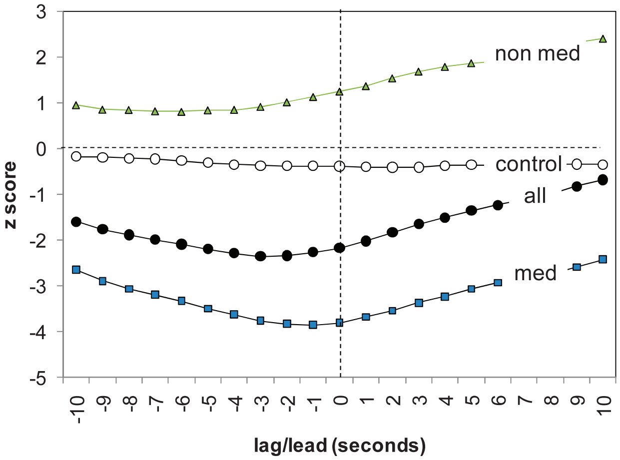

FIG. 8. (Color online) Combined results (weighted Stouffer z) from 121 experimental sessions and 149 control sessions pooled across the first four experiments. "Med" refers to meditators, "non med" to nonmeditators.

TABLE V. Summary of results combined across sessions in experiments 1–4. (See Table I caption for explanations.)

	Number	es	z 0 lag	p 0 lag	z −2 lag	p −2 lag
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
Nonmeditators	41	0.19	1.25	0.89	1.01	0.84
Control	149	−0.03	−0.39	0.35	−0.38	0.35

were measured to provide secondary measures of the predicted effect. In addition, to eliminate the possibility that results observed in the initial experiments might have been due to differential vibrations associated with the computer's spoken instructions, the computer's automated condition assignments were presented over headphones. A total of 50 sessions were preplanned.

A. Method

1. Apparatus

The software used to acquire data and control the experiment was rewritten in Matlab (version 2009b, MathWorks, Natick, MA, USA). This improved the efficiency of the data-acquisition process, which in turn enabled all of the 3000-pixel interference patterns generated during a test session to be captured and stored at 20 camera frames/s. In addition, an electrocortical marker of attention was collected via one electroencephalograph (EEG) channel, which collected data at 512 samples/s. The latter was accomplished using a wireless EEG system which also provided stereo audio channels via headphones (Mindset, NeuroSky, San Jose, CA, USA). This EEG was adapted for our purposes by enhancing its electrode system to provide improved contact with the skin and by positioning its sensor to a left occipital site to avoid frontal-muscle artifacts. The measurement of interest was a neural correlate of focused attention: α band event-related desynchronization (ERD; α refers to the brainwave rhythm 8–12 Hz), which can be detected most readily over the brain's occipital lobe.[26] The idea was to test whether this objective measure of shifts in attention would correlate with changes in the interference pattern.

2. Procedure

All test sessions were conducted in the IONS laboratory. The counterbalancing scheme alternated between attention-toward and attention-away epochs, each lasting for 20 s and repeated 20 times, for a total of

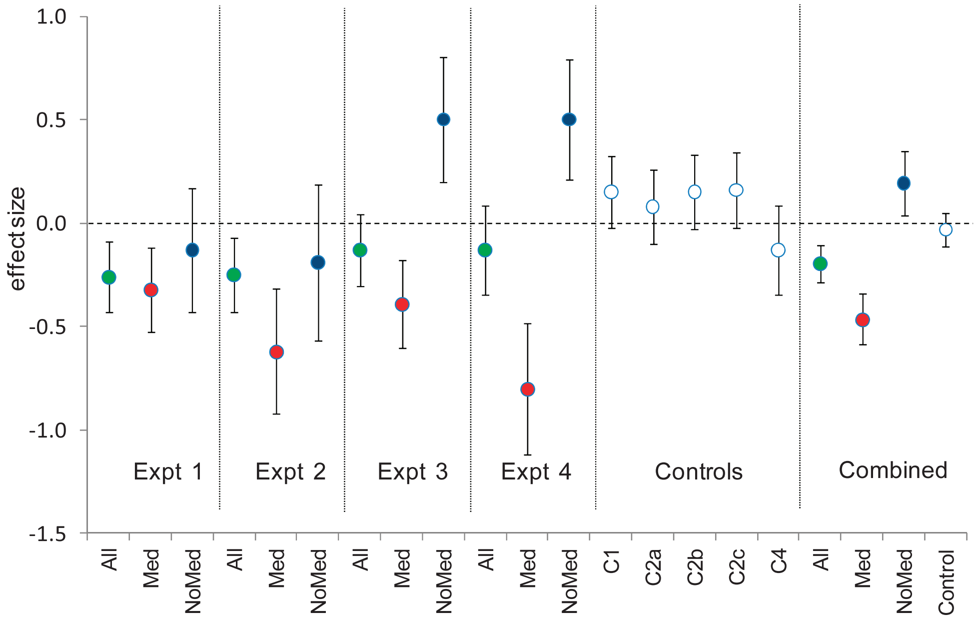

FIG. 9. (Color online) Comparison of effect sizes for the first four experiments and controls. The meditator effect size shown for experiment 2 does not include the Zen Buddhist meditators, as that portion of the study was conducted in a rural location with uncontrolled environmental conditions and erratic electrical-line power.

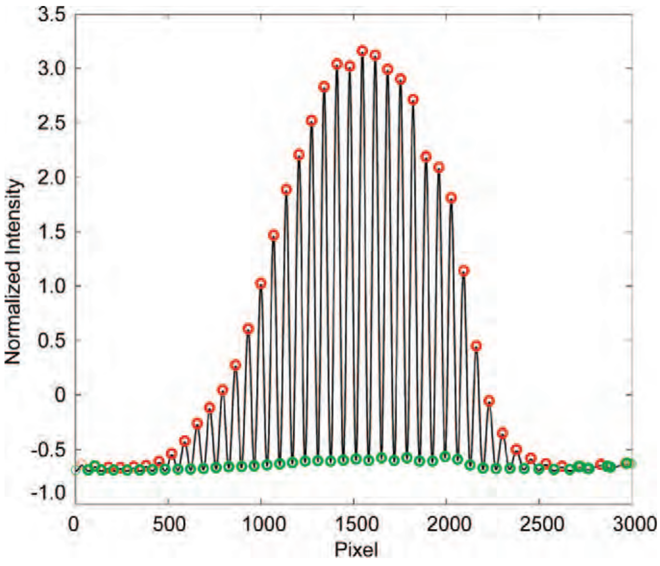

FIG. 10. (Color online) Interference pattern with peaks and troughs identified. Statistical differences in the average heights, compared between the two attention conditions, were evaluated using a nonparametric permutation technique similar to that used for the spectral ratio R.

40 alternating epochs. Each session began after the collection of between 20 and 100 s of baseline data. To ensure that participants understood the nature of the task, prior to each session with a new participant an animated video of the double-slit experiment was shown, followed by a discussion of the task using a drawing of the apparatus to illustrate how the double-slit device worked and where the slits were located in the actual device. As much time as necessary was spent with the participants to ensure that they understood the nature of the task.

Audio performance feedback was provided by associating the playback volume of a Sanskrit chant to variations in the spectral-ratio value R. To do this, the average R value measured during the last 5 s of the previous attention-away epoch was used as a baseline measure, and then the value of R recorded during the attention-toward epoch was compared in real time to that value. To avoid sudden jumps in volume, the volume-adjustment scheme was based on variations in R over a 3 s sliding window. Through this method, during attention-toward periods, the chant played more loudly as R declined. During the attention-away periods, the chant played at a continuous, low-level volume and was not coupled to variations in R. The attention assignments were announced by the computer via prerecorded audio files. Differences in R by attention condition were analyzed as in the earlier experiments; the hypothesis predicted a negative z score.

3. Exploratory measure: Peaks and troughs

The average heights of the interference-pattern troughs and peaks were determined for each camera frame (20 frames/s). To accomplish this, troughs and peaks were determined between pixels 600 and 2400 (see Fig. 10), and then average differences in these values between the two attention conditions were evaluated using a permutation technique similar to that used to assess changes in R.

4. Exploratory measure: Event-related desynchronization (ERD)

To determine the correlation between the electrocortical marker of attention and changes in the interference pattern, for each second of EEG data the spectral power spectrum at 11 Hz (roughly the middle of the α band) was determined, and then the average R value over the same second was calculated. Data for one session thus consisted of 800 pairs of α and R, one pair per second (40 epochs × 20 s/epoch). A Pearson linear correlation between these pairs was determined and then evaluated using a randomized permutation technique, resulting in a z score. These scores were then combined over all sessions.

5. Hypotheses

As in earlier experiments, the principal hypothesis predicted a decline in R. A corollary hypothesis was that the average trough height would rise and the average peak height would drop. A secondary hypothesis predicted that the correlation between α and z would be positive, because as attention increased, both α power and R should decrease, and vice versa.

B. Results

Thirty-one people contributed 51 sessions. The first 50 preplanned sessions, consisting of 858 000 frames of interference-pattern data, are considered here. Fifty control sessions were also conducted. Figure 11 and Table VI indicate that the principal hypothesis was supported with a significant drop in R ($z=-4.48$) and the average peak height ($z=-2.87$) , and a significant rise in the average trough height ($z=3.03$). Effect-size magnitudes were in alignment with the meditator effect sizes observed in the first four experiments.

The experimental effect size obtained in this study was about 3 times as large as that observed in the first four experiments (-0.63 vs. -0.20). This raises the question of whether the counterbalancing scheme of alternating toward and away used in this study might have produced 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 and thus spurious support for the hypothesis.

To test this possibility, the R values recorded in each session were converted into detrended residuals by determining the best-fit linear trend to the data and subtracting that line from the original data. Then the residuals were analyzed and the z scores associated with the original data were compared to the same scores from

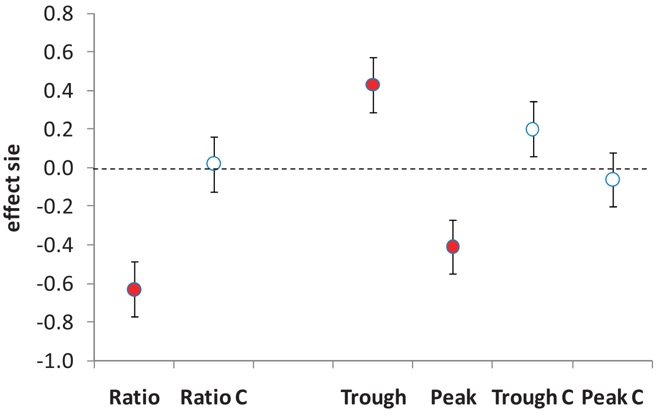

FIG. 11. (Color online) Effect sizes and one standard error of the mean error bars for the spectral ratio R and average trough and peak heights, for experimental and control data in experiment 5.

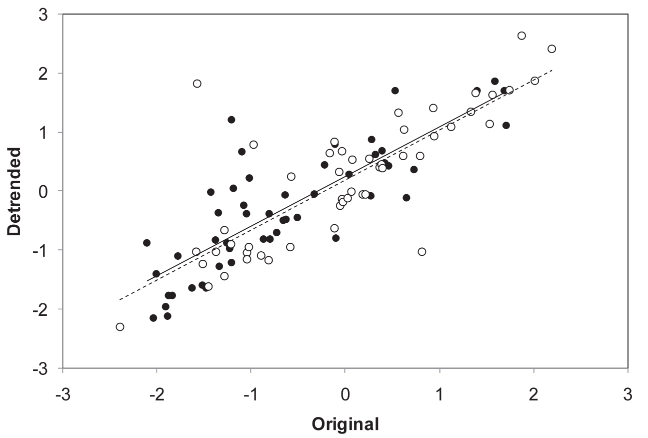

FIG. 12. The solid line shows a linear correlation between the original and detrended experimental data (normalized R values, black dots); the dashed line shows the same for control data (white circles).

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.

The result was a strong positive correlation for both the experimental data (linear correlation $r=0.83$, $p=7\times10^{-14}$; see Fig. 12) and the control data ($r=0.81$, $p=6\times10^{-13}$), indicating that the original results were not due to positive linear drifts. This outcome confirms the analysis of the nonlinear residuals in experiment 1, suggesting that the result of this experiment was not due to mundane drifts in the data.

In preparation for conducting the EEG event-related desynchronization analysis, the first step was to examine the EEG spectrum from 1 to 50 Hz, second by second, in the attention-toward versus attention-away periods. Differences in spectral power were determined using a randomized permutation technique, which resulted in a z score indicating the differential change in α power. The result, shown in Fig. 13, is the expected ERD effect—a decline in spectral power, especially within the α band. This confirms that ERD can be used as a simple electrocortical marker for shifts in attention.

The next step was to calculate the ERD and R values in each session and then the Pearson linear correlation across the 50 pairs of data. The magnitude of the resulting correlation was modestly positive, as predicted (mean $r=0.014$, combined $z(r)=1.4$, $p=0.09$, one-tailed). Of the 50 test sessions, nine were independently associated, with $z(r)>1.65$ ($p=0.05$, one-tailed), which by the exact binomial test is associated with $p=0.0008$. This finding prompted a post hoc examination of the EEG signals in each session, and that in turn identified 19 of the 50 sessions with exceptionally noisy signals, possibly due to intermittent electrode contact with the scalp. Analysis of the α power versus R correlation in the remaining 31 sessions resulted in a combined $z(r)=2.7$ ($p=0.004$, mean $r=0.027$). This finding supports the prediction that an objective measure of shifts in attention would be positively correlated with changes in R, but due to the post hoc nature of this analysis, prudence is warranted.

TABLE VI. Summary of results from experiment 5. (See Table I caption for explanations.)

	Number	*es*	*z* 0 lag
Ratio *R*			
Experiment	50	−0.63	−4.48
Control	50	0.02	0.13
Trough			
Experiment	50	0.43	3.03
Control	50	0.20	1.42
Peak			
Experiment	50	−0.41	−2.87
Control	50	−0.06	−0.41

VIII. EXPERIMENT 6

This study investigated relationships between participants' personalities and beliefs and their performance on the double-slit task. A series of 50 sessions was preplanned with 50 different participants selected to represent a broad range of personality traits, meditation experience, and beliefs. All participants listened to the condition-assignment announcements over headphones.

A. Method

Participants filled out a questionnaire asking about their belief in psychic phenomena, years of meditation, or other attention-training experience, and the Tellegen Absorption Scale, a 34-item questionnaire that measures the degree to which one becomes immersed in a task while focusing.[27] The belief question was employed because experiments conducted since the 1940s have shown that openness to the possibility of extrasensory perception is a reliable predictor of performance in this type of task.[28]

The first half of the sessions in this experiment were conducted in a hotel room at a conference where it was convenient to recruit participants with meditation experience; the remaining sessions were conducted in the IONS laboratory. Both the original and the secondary

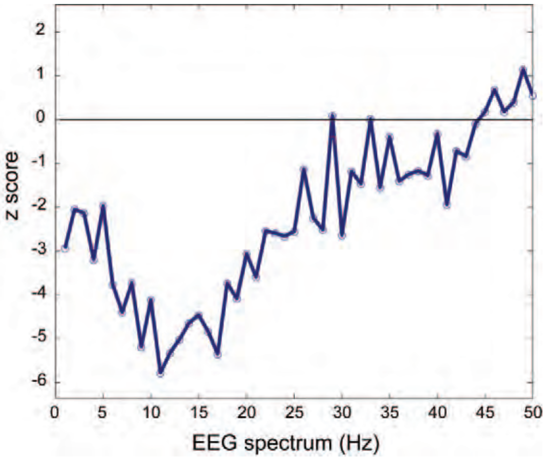

FIG. 13. (Color online) Drop in EEG spectral power when comparing attention-toward versus attention-away conditions across all sessions, in terms of standard normal deviates. Notice the particularly strong drop around the α band (8–12 Hz).

double-slit system were used, to allow two individuals to conduct the study at the same time. In addition, the task instructions were prescripted and read aloud to each participant prior to each session in an attempt to create a more uniform introduction to the task.

There were three other procedural changes from the earlier experiments: (1) To reduce the time required to conduct a session, we did not show the video animation of a double-slit experiment; (2) we used varying-length condition epochs to prevent participants from anticipating when each attention assignment would begin and end (each epoch was assigned a random length from 20 to 30 s); and (3) each session began and ended with a 4 min silent period, during which data continued to be collected.

The principal hypothesis predicted that *R* would drop in attention-toward epochs as compared to attention-away epochs; a corollary was that the average trough height would rise and the average peak height would drop. A secondary hypothesis predicted that correlations between *z* per session and participants' belief in psychic phenomena, capacity for absorption, and years of meditative experience would all be negative.

B. Results

Fifty participants contributed a total of 1.5×10^6 frames of interference data. The effect size associated with *R* was in alignment with the hypothesis, with $es=-0.17$, $z=-1.21$; for the 50 control runs the results were in the opposite direction, with $es=0.20$, $z=1.43$. Effect sizes for the trough and peak measurements were somewhat stronger, with trough $es=0.25$, $z=1.75$, and peak $es=-0.27$, $z=-1.93$. The secondary hypothesis was significantly supported for the correlations between *R* and belief in psychic phenomena ($r=-0.27$, $p=0.03$, one-tailed) and between *R* and capacity for absorption ($r=-0.21$, $p=0.07$, one-tailed), but not for the correlation between *R* and years of meditation experience, which instead resulted in a positive correlation ($r=0.10$, $p=0.75$, one-tailed). As a post hoc examination, given that the average peak measurement produced a stronger result than *R*, the correlation between years of meditation and the peak measurement was examined. This resulted in $r=-0.20$, $p=0.08$, more in alignment with what was observed in previous experiments. Again, since this was a post hoc measure, caution in interpreting this outcome is warranted.

IX. DISCUSSION

Six experiments testing a consciousness collapse hypothesis led to a combined 4.4-sigma effect in the predicted direction ($p=6\times10^{-6}$). Control sessions provided no evidence of procedural or analytical artifacts that might have been responsible for these effects ($z=0.43$, $p=0.67$). Additional investigations examining the possibility that results were due to heat generated by proximity of the body, or sound vibrations associated with announcements of the condition assignments or performance feedback, or systematic drifts or oscillations, also failed to identify viable artifacts.

Figure 14 summarizes the ΔR effect sizes in the experiments, Fig. 15 shows a cumulative *z* score for the same data, and Fig. 16 shows a similar analysis for meditator versus nonmeditator sessions. Twenty-nine sessions collected in the last two experiments were not part of the preplanned design (labeled "extra" in Fig. 15), but are included in the final analysis for completeness.

The average effect size per session over the first four experiments was $es=-0.20$. 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 100 sessions. The results observed in the 100 sessions of experiments 5 and 6 surpassed this prediction, mainly due to the stronger effect size observed in experiment 5. That outcome may have reflected our intention to optimize results by (a) conducting all sessions in the controlled laboratory environment, (b) implicitly reminding participants through use of an EEG monitoring system that paying attention during the session was important, (c) ensuring that those participants understood what was expected of them by showing an animation of a double-slit experiment and then spending as much time as was necessary to discuss the nature of the task, and (d) preferring participants with meditation experience and openness to the nature of the task. By contrast, in experiment 6 we recruited people with a broad range of *a priori* beliefs and meditation experience, and we read instructions from a fixed script to decrease the time required to conduct each session.

A. Potential environmental factor

A factor that was possibly responsible for some of the performance variance observed across test sessions was nanotesla-scale fluctuations in the Earth's geomagnetic field (GMF). This variable has been shown to be a significant factor in many areas of human performance,

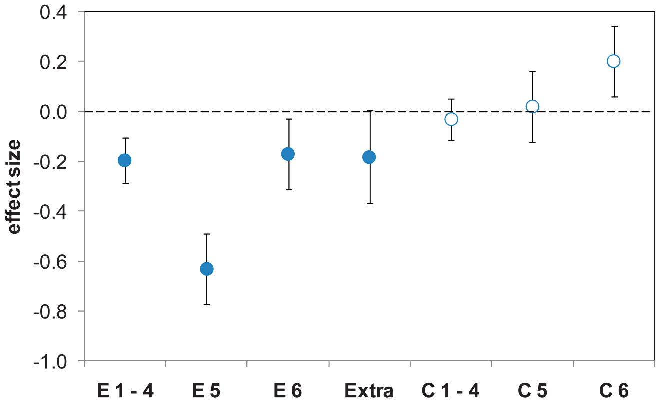

FIG. 14. (Color online) Effect sizes and one standard error of the mean error bars in all experiments and controls, and across 29 extra sessions that were not part of the preplanned designs of experiments 5 and 6 (labeled "Extra").

including stock-market behavior,[29] airplane crashes,[30] suicides,[31] cardiac health,[32] and—of special relevance to the present studies—a greater frequency of reported spontaneous psychic experiences as well as enhanced performance in controlled extrasensory-perception tasks.[33] To explore whether this factor might have influenced performance in the present experiments, the GMF ap index (a measure of global geomagnetic activity) was retrieved for the day of each test session.[34] Based on previous GMF correlation studies, the prediction was that during days of quiet GMF, performance on the double-slit task would increase (indicated by a decrease in R) as compared to days with noisier GMF.

Figure 17 shows the results in terms of combined z score for sessions conducted on the N quietest and N stormiest days, with N representing the GMF contrast of interest. For example, a contrast of $N=7$ refers to all sessions conducted during days with the seven largest and seven smallest ap values and to combine the z scores associated with changes in R obtained in those sessions. The figure indicates that for high GMF contrasts there was, as predicted, a strong difference in experimental performance, with better results on lower-ap days than on higher-ap days. For $N=7$, the mean natural log of GMF on the quietest days was $\ln(\text{ap})=0.49$, and the session z score combined across those days was $z=-2.3$. By contrast, the mean for the seven noisiest-GMF days was $\ln(\text{ap})=3.30$, and the combined result for sessions run on those days was $z=1.97$. The statistical difference between sessions conducted on high- and low-GMF days was $z=-3.0$. Figure 17 indicates that the direction of this difference was maintained regardless of the magnitude of the contrast, suggesting that this performance difference was indeed associated with GMF flux. Of greater importance, it indicates that a variable known to correlate with performance in similar "extrasensory" tasks was also observed in the present experiments.

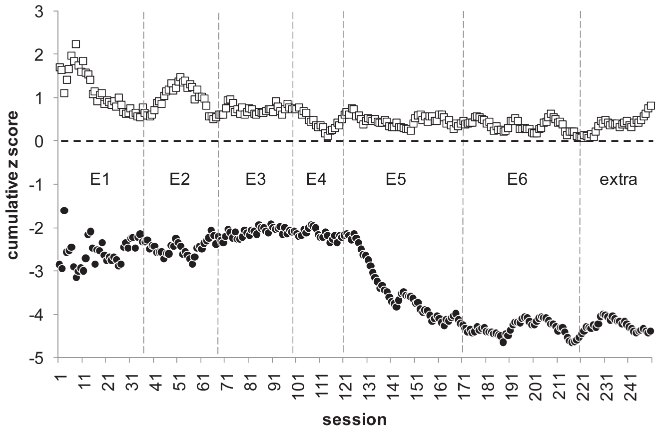

FIG. 15. Cumulative z score for all 250 experimental and control sessions.

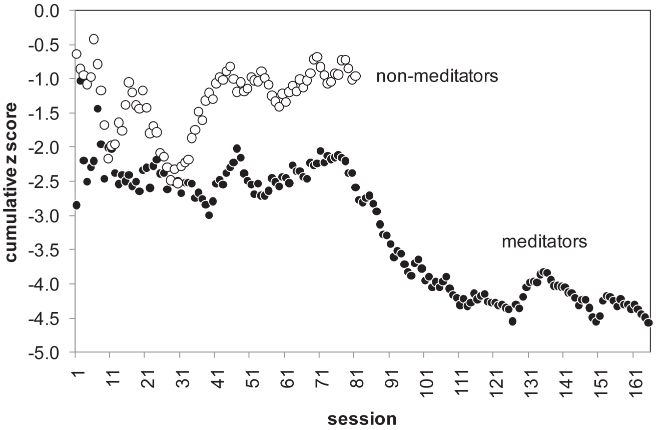

FIG. 16. Cumulative z score for meditators and nonmeditators across all six experiments.

B. These studies in context

Because it is central to interpretations of quantum mechanics, the physics literature abounds with philo-

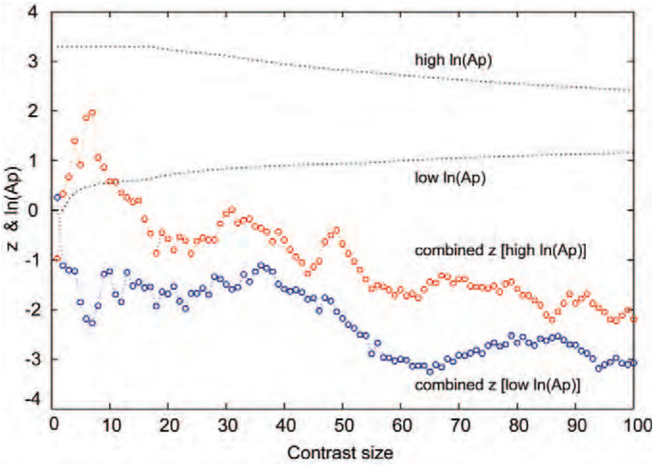

FIG. 17. (Color online) Examination of possible daily influence of the geomagnetic field on session performance across the six experiments. A contrast size of, say, 7 refers to sessions conducted on days with the seven largest and seven smallest ln (ap) values (natural log of daily ap index); these values are indicated along the x axis by the upper dashed lines labeled "high ln (ap)" and "low ln (ap)." The combined experimental z scores for sessions run on those dates are shown in the bottom dotted lines.

sophical and theoretical discussions about the QMP, including speculations about the role of consciousness. One might expect to find a correspondingly robust experimental literature testing these ideas, but it is not so, and the reason is not surprising: The notion that consciousness may be related to the formation of physical reality has come to be associated more with medieval magic and so-called New Age ideas than it is with sober science. As a result, it is safer for one's scientific career to avoid associating with such dubious topics and subsequently rare to find experiments examining these ideas in the physics literature. Indeed, the taboo is so robust that until recently it had extended to any test of the foundations of quantum theory. For more than 50 years such studies were considered unsuitable for serious investigators.[35] As Freire noted in discussing the history of tests of Bell's theorem,

> Some of the physicists who decided not to hire Clauser were influenced by the prejudice that experiments on hidden variables were not "real physics." His former adviser, P. Thaddeus, wrote letters warning people not to hire Clauser to do experiments on hidden variables in quantum mechanics as it was "junk science," a view shared by other potential employers.[35(p.284)]

However, this is not to say that the scholarly literature is mute on this matter. A century-long empirical literature can be found in the controversial domain of parapsychology, which focuses on the interface between mind and matter. Here we find over a thousand peer-reviewed studies reporting (a) experiments testing the effects of intention on the statistical behavior of random events derived from quantum fluctuations,[36,37] (b) studies involving macroscopic random systems such as tossed dice and human physiology as the targets of intentional influence,[38] (c) experiments involving sequential observations to see whether a second observer could detect if a quantum event had been observed by a first observer, or if time-delayed observations would result in similar effects,[39–41] and (d) experiments investigating conscious influence on nonliving systems ranging from molecular bonds in water to the behavior of photons in interferometers.[42]

Much of this literature has appeared in discipline-specific journals, but given the controversial nature of the topic, it is worth noting that some of it has also appeared in better-known outlets including the *British Journal of Psychology*,[38] *Science*,[43] *Nature*,[44] *Proceedings of the IEEE*, [45] *Neuroscience Letters*,[46] *Psychological Bulletin*,[47,48] and others. Cumulatively, these experiments suggest that mind–matter interactions occur in a broad range of physical target systems. Observed effects tend to be small in absolute magnitude and are not trivially easy to repeat on demand, but high variance and concomitant difficulties in replication are to be expected because all of these studies necessarily involved focused human attention or intention. As with any form of human performance, the ability to focus attention varies substantially not just from one person to the next, but within each individual from day to day and throughout the course of a single day.[49,50] Variables influencing the ability to perform mental tasks go beyond simple factors such as nervous-system arousal and distractions; they include when one last dined and what was consumed,[51] interactions between personal beliefs and the nature of the task,[52] the state of the geomagnetic field, and so on. Such 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 some properties of quantum objects are not completely independent of human consciousness, then such a study cannot be conducted as a conventional physics experiment, nor can be it conducted as a conventional psychology experiment. The former tends to ignore subjectivity and the latter tends to ignore objectivity.

In an attempt to accommodate both sides of the proposed relationship, we designed a physical system with interference fringes as stable as possible, and we also cultivated a comfortable test setting, encouraged a sense of openness to the idea of extended forms of consciousness, selected participants with practice in focusing their attention, and spent generous amounts of time discussing the nature of the task with the participants. The superior results observed with meditators suggest that in spite of unavoidable performance variance, it may be possible in future studies to identify those aspects of attention and intention that are most important in producing the hypothesized effect.

It should be noted that some meditation styles, such as mantra repetition, tend to train for focused or concentrated attention, while others, such as mindfulness meditation, tend to expand one's attentional capacities.[53] No attempt was made in the present studies to assess differences among reported meditation styles, or to independently measure participants' capacity for sustaining focused attention. However, it is not unreasonable to expect that future studies might find that different meditative styles lead to different outcomes. In addition, measuring participants' capacity for sustaining attention, investigating other brain and behavioral correlates of performance, using single-photon designs, and developing more refined analytical procedures would all be useful directions to pursue.

In sum, the results of the present experiments appear to be consistent with a consciousness-related interpretation of the QMP. Given the ontological and epistemological challenges presented by such an interpretation, more research will be required to confirm, systematically replicate, and extend these findings.

ACKNOWLEDGMENTS

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