Psychophysical interactions with a double-slit interference pattern

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Abstract: Previously reported experiments suggested that interference patterns generated by a double-slit optical system were perturbed by a psychophysical (i.e., mind–matter) interaction. Three new experiments were conducted to further investigate this phenomenon. The first study consisted of 50 half-hour test sessions where participants concentrated their attention-toward or -away from a double-slit system located 3 m away. The spectral magnitude and phase associated with the double-slit component of the interference pattern were compared between the two attention conditions, and the combined results provided evidence for an interaction (effect size $= -0.73 \pm 0.14$, $p = 2.4 \times 10^{-7}$). One hundred control sessions using the same equipment, protocol and analysis, but without participants present, showed no effect (effect size $= 0.04 \pm 0.10$, $p = 0.71$). A Fraunhofer diffraction model was used to explore various interpretations of this outcome. This analysis suggested that the distribution of light between the two slits and the horizontal stability of the laser beam were the principle components of the optical system that were perturbed. The second experiment used a duplicate double-slit system and similar test protocol, but it was conducted over the Internet by streaming data to participants' web browsers. Some 685 people from six continents contributed 2089 experimental sessions. Results were similar to those observed in the first experiment, but smaller in magnitude (effect size $= -0.09 \pm 0.02$, $p = 2.6 \times 10^{-6}$). Data from 2303 control sessions, conducted automatically every 2 h using the same equipment but without observers showed no effect (effect size $= -0.01 \pm 0.02$, $p = 0.61$). Distance between participants and the optical system, ranging from 1 km to 18,000 km, showed no correlation with experimental effect size. The third experiment used a newly designed double-slit system, a revised test protocol, and a simpler method of statistical analysis. Twenty sessions contributed by 10 participants successfully replicated the interaction effect observed in the first two studies (effect size $= -0.62 \pm 0.22$, $p = 0.006$). © *2013 Physics Essays Publication*. [http://dx.doi.org/10.4006/0836-1398-26.4.553]

Résumé: Des expériences réalisées précédemment suggèrent que des franges d'interférences générées par un système de double fente optique peuvent être perturbées par des interactions psycho-physiques (c'est-à-dire des interactions entre conscience et matière). Trois nouvelles expériences ont été menées pour étudier ce phénomène. Dans la première étude, au cours de 50 séances d'une demi heure chacune, des participants ont concentré leurs attentions soit pour influencer un système de double fente située à 3 m de distance, soit pour ignorer ce même système. L'ampleur et la phase spectrale associée aux franges d'interférence ont été comparés entre les deux conditions de focalisation de l'attention, et les résultats combinés sont compatibles avec l'hypothèse d'une interaction entre conscience et matière (taille d'effet $= -0.73 \pm 0.14$, $p = 2.4 \times 10^{-7}$). De plus, l'effet n'est pas présent quand la même analyse est effectuée sur cents sessions contrôles utilisant le même équipement et le même protocole, mais fonctionnant en l'absence de participants (taille d'effet $= 0.04 \pm 0.10$, $p = 0.71$). Un modèle de diffraction de Fraunhofer utilisé pour explorer différentes interprétations de ce résultat suggère que la distribution de la lumière entre les deux fentes et la stabilité horizontale du faisceau laser sont les principaux composants du système optique qui ont été perturbés. La seconde expérience utilise un système de double fente et un protocole de test similaire, mais elle a été menée sur Internet en envoyant en temps réel les données du système de double fente aux navigateurs Web des participants. 685 personnes provenant de six continents ont contribué 2089 sessions expérimentales. Les résultats sont similaires à la première expérience mais la taille d'effet est de plus faible amplitude (taille d'effet $= -0.09 \pm 0.02$, $p = 2.6 \times 10^{-6}$). Les données de 2303 sessions de contrôle, réalisé automatiquement toutes les deux heures en utilisant le même équipement mais sans observateurs n'ont montré aucun effet (taille d'effet $= -0.01 \pm 0.02$, $p = 0.61$). La distance entre les participants et le système optique, qui va de 1 km à 18,000 km, n'est pas corrélée avec la taille de l'effet expérimental. La troisième expérience utilise un système

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de double fente nouvellement conçu, un protocole modifié, et une méthode simple d'analyse statistique. Vingt séances réalisées par 10 participants ont permis de reproduire l'effet d'interaction observé dans les deux premières études (taille d'effet $= -0.52 \pm 0.22$, $p = 0.02$).

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

I. INTRODUCTION

Elementary quantum objects behave differently when observed than when unobserved.[1] This can easily be demonstrated in a double-slit optical system by using a detector to determine the path that photons take through the two slits. When "which-path" information is obtained, photons behave in a particle-like fashion, otherwise they behave in a wave-like fashion.[2] The shift from wave to particle is reflected by a decline in interference in the pattern of light produced by the double-slit apparatus.

Numerous interpretations of this observational sensitivity, known as the quantum measurement problem (QMP), have been proposed. They range from the QMP presents a severe threat to the foundations of quantum theory, to the QMP is a mere pseudoproblem.[3–6] So far there is little consensus on which interpretation is most adequate.[7] The chronic state of confusion was reaffirmed in a January 2013 news item in *Nature*, which reported an informal poll taken at a 2011 conference on "Quantum Physics and the Nature of Reality."[8] The poll indicated that 80 years after the development of quantum theory there is still no agreement on interpretations of the QMP among scientists and scholars who specialize in studying the foundations of quantum reality. For example, one of the questions asked in the poll was about the role of the observer in quantum theory: The observer (a) is a complex quantum system, (b) plays no role whatsoever, (c) has a role in the formalism but no physical role, or (d) plays an important physical role (e.g., wave-function collapse by consciousness). Again the responses indicated a lack of consensus, with about the same number of respondents asserting that the observer played either no role or a critical role.

One reason that such fundamental questions remain unresolved is due to a lack of empirical evidence that might assist in informing the debate. The experiments reported here and in earlier publications were designed to provide such data. The approach we took was to probe the behavior of the interference pattern produced by a double-slit optical system to see if focused attention alone might alter the interference pattern in predictable ways. To do this, we asked individuals to attempt to gain which-path information from a double-slit system using so-called extrasensory perception (ESP). While the idea of ESP is perpetually controversial because there are no well-accepted explanations for such phenomena, based on a growing experimental literature it appears that the existential portion of the debate may be nearing a denouement. The cumulative evidence in favor of such a phenomenon has systematically improved over the last century, and articles reporting these studies are increasingly appearing in mainstream journals.[9–14]

A. Background

In earlier publications, we reported a series of psychophysical interaction experiments using optical interferometers.[15,16] Participants in those studies were asked to imagine that they could mentally perceive the movement of photons in an interferometer so as to gain which-path information, or to mentally "push" the photons to influence their path. The behavior of the interference pattern was then compared between counterbalanced attention-toward versus attention-away conditions.

The first study involved a Michelson interferometer; that was followed by six experiments using a Young-type double-slit system.[9,10] The Michelson study resulted in a statistically significant difference in the interference pattern between the two attention conditions ($p = 0.002$), with most of the effects due to 9 of 18 total sessions involving experienced meditators as participants (meditators $p = 9.4 \times 10^{-6}$). Control tests using the same setup in the same location but with no observers present resulted in a null effect. The double-slit experiments showed a similar outcome when participants were observing (overall $z = -4.36$, $p = 6 \times 10^{-6}$), and null results in control conditions without observers ($z = 0.43$, $p = 0.67$). Examination of the experimental protocol, analytical procedures, and variations in temperature, vibration, and signal drift revealed no artifacts that could adequately account for the observed effects.

The experiments reported here were designed to (a) replicate previous results and model the data to analytically explore how psychophysical interactions might perturb an interference pattern, (b) study the role of distance between participants and the optical system, and (c) replicate the effect using a more stable interferometer and a simpler analytical approach.

II. EXPERIMENT 1

A. Method

1. Double-slit system

A 5 mW linearly polarized HeNe laser beam (Model 25 LHP 151-249, 632.8 nm wavelength, TEM_{00}, Melles-Griot, Albuquerque, NM, USA) was passed through two 10% transmission neutral density filters (Rolyn Optics, Covina, CA), and then through two slits etched in a metal foil slide with slit widths of 10 μm each and separated by 200 μm (Lenox Laser, Glen Arm, MD, USA). The interference pattern was recorded by a 3000 pixel CCD line camera with a pixel size of 7×200 μm (7 μm pitch) and 12-bit A-D resolution (Thorlabs Model LC1-USB, Newton, NJ, USA). The camera was located 14.0 cm from the slits,[1] and a camera snapshot or

[1] An earlier publication mistakenly listed this distance as 10.4 cm.

frame recorded the interference pattern by integrating light intensity for 40 ms, allowing for collection of 20 frames per second.

The optical apparatus was housed inside an optically sealed, custom-machined aluminum housing, painted matte black inside and out. The laser and camera were powered continuously throughout the experiment to avoid warm-up fluctuations, and the experiment was controlled by a Microsoft Windows 7 computer running a program written in MATLAB (version 2009 b, MathWorks, Natick, MA, USA), and augmented by software libraries to interface the Thorlabs camera to the computer.

2. Environment

All test sessions were conducted inside an electromagnetically shielded chamber (double steel-walled, 8 feet per side, 2800 pounds, Series 81 Solid Cell chamber, ETS-Lindgren Cedar Park, TX, USA), and electrical line power was conditioned by an electromagnetic interference filter (ETS-Lindgren filter LRW-1050-S1). The interior walls and ceiling of the chamber were covered with fabric and the floor was covered with antistatic carpeting. After the participant had settled in, a research assistant explained the task and then left the chamber and shut the door.

3. Participants

Twenty-one individuals recruited for the test were selected based either on their superior performance in previous experiments of this type,[15,16] or because they maintained an active meditation practice or other mental discipline that requires focused attention, such as musician, intentional healer, or artist. Ages of the recruited participants ranged from 22 to 63 (mean 47). As a group they had no distinguishing features compared with numerous demographic factors (gender, race, income, education, profession, etc.), but one factor was strongly deviant from the population norm—a personality trait called *absorption*. This refers to the capacity to become deeply involved in sensory or imaginative experiences, and in extreme cases to lose awareness of everything except for a single object of attention. Of particular relevance to the present study is that the trait of high absorption is commonly associated with experiential reports of expanded awareness and self-transcendence. This group of participants was substantially above the population norm for absorption, as measured by the Tellegen Absorption Scale ($z = 3.5$, $p = 0.0003$).[17]

4. Procedure

Participants filled out an informed consent describing the nature of the task, then one at a time a research assistant invited them into the shielded chamber. The optical apparatus was described, including the location inside the device where the double-slit was located. Then the participant was instructed to sit in a chair about 3 m from the optical system and asked to remain seated and to not approach the optical system at any time during the test session.

The research assistant then told participants that when they heard a recorded voice instructing them to "concentrate," that they should focus their attention on the two slits located inside the optical system. It was explained that this task was an act of imagination and that they would not be looking at the actual slits with their eyes. Most of the participants were selected based on their previous performance on this task, so they were familiar with the procedure. New participants were advised that if they preferred they could mentally try to block one of the two slits, or to "become one with" the optical system in a contemplative way, or to mentally push the laser beam so as to cause it to go through one slit rather than both. The precise form of interaction was left up to each participant and could be modified at their discretion.

At this point, the participant put on noise-cancelling headphones and the research assistant left the shielded chamber. Shortly thereafter, the participant heard a recorded voice welcoming them, followed by instructions to relax for a minute while a presession baseline was recorded from the double-slit system. Then the recording announced the beginning of each test condition. Attention-toward periods were announced with the phrase "now please concentrate," and attention-away periods with the phrase "now please relax." At the end of the test session, the recorded voice invited the participant to relax for a minute while a postsession baseline from the optical system was obtained.

Concentration and relax epochs lasted 30 s plus an additional 0–9 s determined uniformly at random on each successive epoch. Random epoch lengths were used to encourage participants to remain alert by preventing them from accommodating to fixed time periods; it also was useful in avoiding spurious synchrony between the length of the epochs and inherent power or frequency oscillations in the laser.

Each test session consisted of 40 epochs presented in a counterbalanced AB order, where A and B refer to attention-toward (i.e., concentrate) and attention-away (relax), respectively. Including the pre and postbaseline data, on average one test session lasted about 25 min, during which camera frames were recorded at 20 per second, for a total of about 30,000 frames per session.

To assist participants in focusing on the task, real-time performance feedback was provided during the concentrate epochs. To do this, the volume of a richly harmonic droning tone was controlled by the ratio between the double-slit and single-slit spectral magnitudes (as described below). When that value declined the volume increased, and vice versa. To avoid sudden changes in volume, the ratio values were averaged over 3 s. During relaxation periods, the droning tone was set to a uniformly low volume and uncoupled from variations in the ratio value.

5. Data preprocessing

Interference pattern data recorded during the experimental sessions were preprocessed in five steps:

1. The interference pattern recorded from each camera frame was decomposed into its spatial wavenumbers

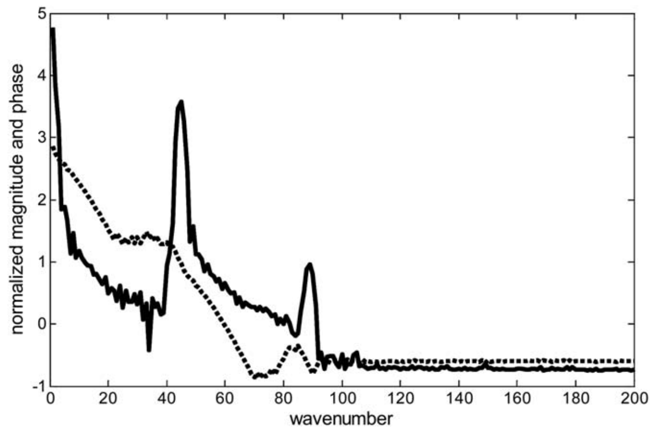

FIG. 1. Mean normalized log 10 spectral magnitude (solid line) and mean normalized unwrapped phase (dotted line) for wavenumbers 1–200, averaged across a sample dataset of 30,000 interference patterns. The magnitude peak at wavenumber 2 corresponds to the diffraction pattern associated with each slit; the peak at wavenumber 45 corresponds to the interference pattern created by both slits; the smaller peak at wavenumber 90 is a harmonic of the peak at 45.

using MATLAB's discrete Fast Fourier Transform (FFT) function.

2. The complex numbers resulting from the FFT were separated into spectral magnitude with the MATLAB *abs* function and spectral phase with the MATLAB *angle* function.
3. Magnitude was log 10 transformed to reduce distribution skew, and phase was adjusted using the MATLAB *unwrap* function, which smoothes angular discontinuities that can arise in successive phase measurements. That is, because phase is bound within the unit circle, it is possible for angles that are close to each other in successive measurements to apparently jump from say, $+\pi$ to $-\pi$. The *unwrap* function removes these jumps. Figure 1 shows the mean normalized log-transformed magnitude and unwrapped phase for the first 200 wavenumbers, averaged over 30,000 camera frames.
4. Log-transformed magnitude was detrended using a least-squares linear fit between the spectral peaks associated with single-slit diffraction and double-slit interference, specifically between the nearly linear portion of the spectrum between wavenumbers 14 and 39 (as shown in Fig. 1). This midspectrum detrending was used to reduce noise associated with oscillations in laser output intensity associated with thermal expansion and contraction in the HeNe laser tube, and with laser mode-hopping (see Fig. 2).
5. To reduce autocorrelations between successive samples due to potential signal drift, all double-slit magnitude and phase samples (at wavenumber 45) were linearly detrended over the course of each session (see Fig. 3).

It is essential to note that these preprocessing transformations were applied to the data uniformly without regard to the assigned attention conditions. That is, the objective (optical system) and subjective (attention instructions) components of this experiment were strictly independent.

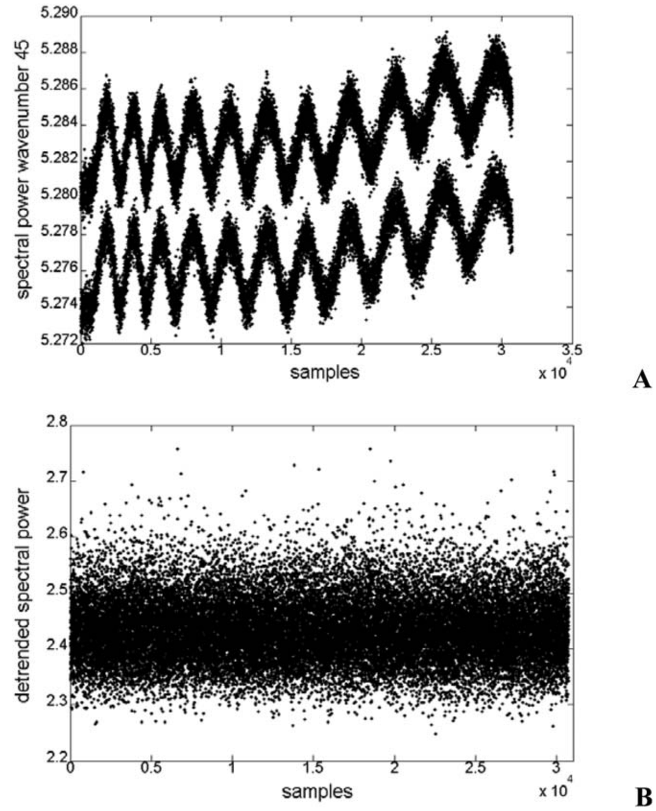

FIG. 2. (A) Double-slit spectral magnitude at wavenumber 45 across 30,000 camera frames (one sample per frame), showing bimodal distribution. (B) Same after linear detrending the spectral magnitude between single and double-slit peaks (from wavenumbers 14 to 39).

6. Analysis

Analyses were performed on the preprocessed data and all probabilities reported are two-tailed. Psychophysical interactions were assessed by calculating the difference between double-slit spectral magnitude (DSM) recorded during all concentrate epochs (C) versus the same measure recorded during all relax epochs (R) over the course of a given test session. The same method was followed for calculating the overall C-R difference in phase. These differences

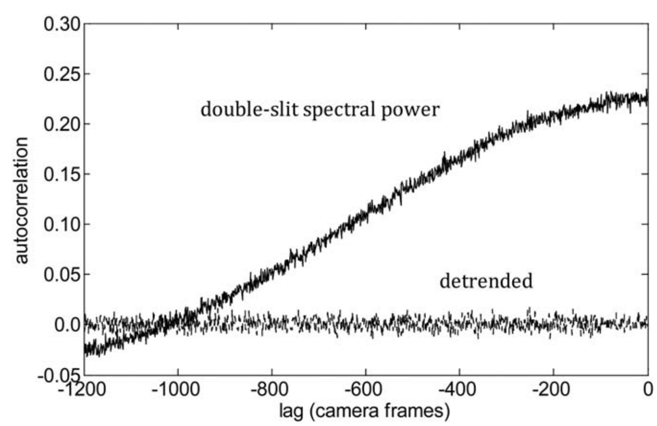

FIG. 3. Autocorrelations up to lag 1200 in successive samples of double-slit magnitude (i.e., wavenumber 45) and autocorrelations after linearly detrending.

were assessed separately for each of the 50 test sessions using a nonparametric Mann–Whitney U-test; one for spectral magnitude and one for phase. Note that step 5 in the data preprocessing scheme removed sample autocorrelations, in accordance with the requirement of independence of samples in a Mann–Whitney U-test.[18] The outcomes of the two Mann–Whitney U-tests per test session, each expressed in terms of a z score, were combined *within* each session as a composite z score, i.e., $z = (z_{mag} + z_{phase})/\sqrt{2}$, and the resulting composite z scores were combined *across* sessions as a Stouffer z score (i.e., $sz = \sum_{i=1}^{n} z_i/\sqrt{n}$, where n is the number of sessions and sz is distributed as a z score).

To gain further confidence that this statistical procedure did not introduce an unanticipated artifact, the final Stouffer z composite score was compared with chance expectation of a zero difference using a nonparametric bootstrap test. This procedure compared the original Stouffer z to a distribution of 10,000 identically constructed composite Stouffer z scores formed by randomly permuting the original C and R assignments within each session. The outcome of this process was a new z score formed as $z = (sz - \mu)/\sigma$, where μ was the mean and σ the standard deviation of the distribution of bootstrap-generated composite scores. Under the null hypothesis of no psychophysical interaction, this differential composite measure of double-slit magnitude and phase should be zero.

Besides calculating this composite score, an additional analysis was deemed to be useful. The hypothesized psychophysical effect is assumed to be associated with human attention, which suggests that it should take a few seconds for participants to reorient their attention when switching between mental tasks. As a result, the composite z score was predicted to be larger (in an absolute sense) after lagging the data a few seconds,[19] and more specifically, based on our previously reported studies the lag would take about 3 s. Thus, the composite z score was recalculated after lagging the data with respect to the moment when the attention instructions were provided.

Conducting repeated statistical tests requires adjustment for multiple comparisons, so assuming that the maximum difference would be observed from about 2–4 s, a conservative Bonferroni correction would require $p = 0.025/3 = 0.008$ (based on two-tailed probabilities), or $z = 2.4$ as a threshold for declaring a statistically significant effect.

B. Results

Analysis of 1.5×10^6 frames of interference pattern data from 50 planned test sessions contributed by the 21 participants showed a significant deviation in the composite z score with the maximum effect observed with data lagged 3 s ($z = -5.16$, $es = -0.73 \pm 0.14$, $p = 2.4 \times 10^{-7}$, where effect size $es = z/\sqrt{N}$, standard error of $es = 1/\sqrt{N}$, and $N = 50$). See Fig. 4 for z scores for spectral magnitude and phase lagged from 0 to -15 s. The identical experimental and analytical methods applied to data collected in 100 control sessions in the same environment and with the same equipment resulted in a null effect at a lag of 3 s ($z = 0.37$, $es = 0.04 \pm 0.10$, $p = 0.71$). Figure 5 shows the results for the composite z score.

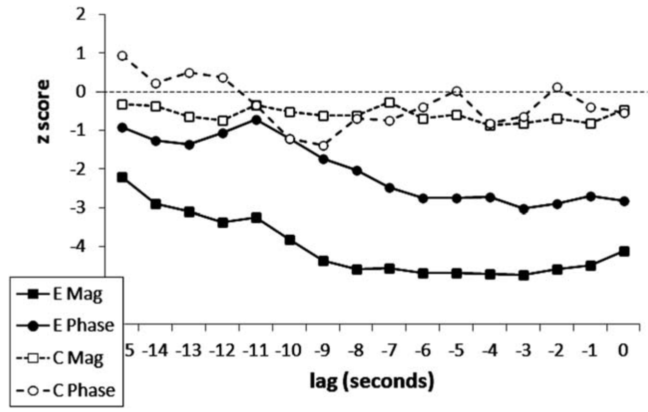

FIG. 4. Mann–Whitney U-test comparisons for differences between concentrate and relax conditions for spectral magnitude and phase, recorded over 50 experimental (E) and 100 control (C) sessions, and recalculated for data lagged from 0 to -15 s from the moment when the attention instructions were given, to show these results in temporal context. Based on earlier studies, the optimal value was predicted to fall between -2 and -4 s of lag to account for delays in human attention-switching.

C. Modeling

This experiment suggested that DSM was perturbed in accordance with a psychophysical interaction hypothesis. To explore how this might have occurred, we modeled a double-slit system based on data recorded during the experiment and then tested how parameters of that model changed over the course of the experiment.

To optimize the potential yield of the modeling effort, only those experimental test sessions that resulted in statistically significant outcomes were examined (i.e., the differential comparison of interest in the session resulted in $p < 0.05$, two-tailed). Twelve such sessions were identified. Obtaining 12 or more significant sessions out of 50 is associated with $p < 5 \times 10^{-6}$ by exact binomial calculation, thus as a set those sessions provided a robust database with which to analyze the modeled parameters.

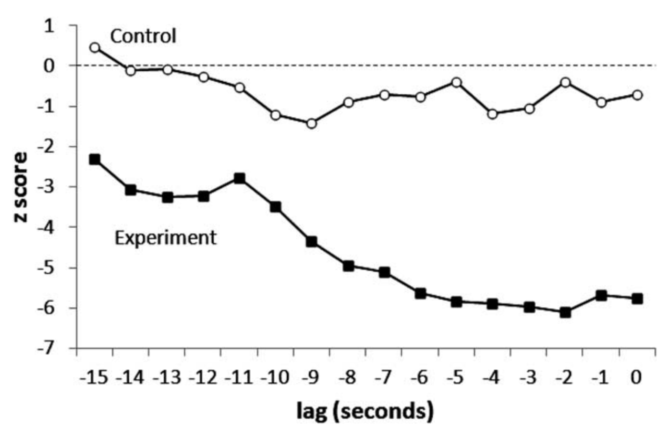

FIG. 5. Composite z scores for magnitude and phase, evaluated by a nonparametric bootstrap procedure, for 50 experimental and 100 control sessions.

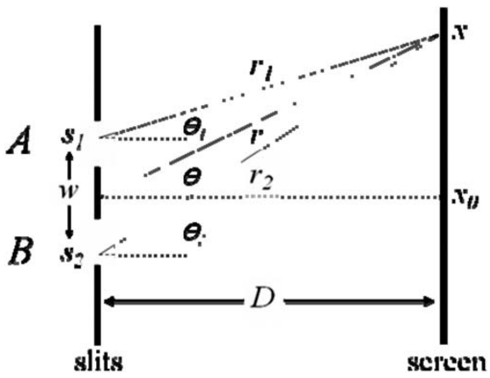

FIG. 6. Parameters associated with a Fraunhofer model of a double-slit optical system. Parameters A and B are electric field strengths associated with the light beam passing through slits 1 and 2, respectively. See text for description of the other parameters.

1. Equations

We used a model of a double-slit optical system based on the Fraunhofer approximation to Fresnel diffraction, as illustrated in Fig. 6.

In Fig. 6, light with electric field strength A passes through slit s_1 (call this field E_1), and likewise B through s_2 (E_2). The slits are separated by distance w and they are both located a distance D from the screen. The electrical field at location x on the screen is the sum of fields E_1 and E_2, which are defined as

$$E_1 = A\frac{s_1 e^{ikr_1}}{r_1}\frac{\sin\beta_1}{\beta_1} \quad \text{and} \quad E_2 = B\frac{s_2 e^{ikr_2}}{r_2}\frac{\sin\beta_2}{\beta_2}, \tag{1}$$

and where $\beta_1 = \frac{1}{2}ks_1\sin\theta_1 = \frac{1}{2}ks_1(x_1/r_1) = \frac{1}{2}ks_1\left(x_1/\sqrt{D^2+x_1^2}\right)$, similarly for β_2, k is the wave number $2\pi/\lambda$, where λ is the wavelength of light, and $x_1 = x - \frac{1}{2}(w+s_1)$ and $x_2 = x - \frac{1}{2}(w+s_2)$.

The intensity of light I on the screen at x is the sum of the two field strengths squared, $I(x) = (E_1 + E_2)^2$, and thus,

$$\begin{aligned} I(x) &= \left[A\frac{s_1 e^{ikr_1}}{r_1}\frac{\sin\beta_1}{\beta_1} + B\frac{s_2 e^{ikr_2}}{r_2}\frac{\sin\beta_2}{\beta_2}\right]^2 \\ &= A^2\left[\frac{s_1\sin\beta_1}{r_1\beta_1}\right]^2 + B^2\left[\frac{s_2\sin\beta_2}{r_2\beta_2}\right]^2 \\ &\quad + 2AB\frac{s_1\sin\beta_1}{r_1\beta_1}\frac{s_2\sin\beta_2}{r_2\beta_2}\cos(k(r_2 - r_1)). \end{aligned} \tag{2}$$

From Eq. (2), we see that the intensity I at the screen in Eq. (2) is the sum of three intensities, the diffraction patterns from each of the two slits plus interference between the slits, or simply

$$I = I_{s1} + I_{s2} + I_{\text{int}}. \tag{3}$$

Each slit in our system was specified as 10 μm (10^{-6} m) in width with slits separated by 200 μm (with $\pm$ 10% tolerances). The wavelength of the HeNe laser light was 632.8 nm, and the distance from the slits to the camera was 14 cm. This set of parameters was analytically refined using a nonlinear curve fitting procedure[2] to fit the idealized model to the interference pattern based on the mean of 10,000 camera images collected under calibration conditions. The electric field parameters A and B in Eq. (2) were replaced by $A \times A_u$ and $B \times B_u$, where A_u and B_u are the values determined from calibration, so that A and B were 1.0 for calibration data, thus allowing easy recognition of deviations from calibration. And similarly, x_0 (the location of the interference pattern maximum, as shown in Fig. 6) represents the deviation from the calibration value.

The best fit for the physical configuration of our system was obtained with parameters $s_1 = 11.4\,\mu$m, $s_2 = 10.0\,\mu$m, $w = 186\,\mu$m, $x_0 = 169\,\mu$m, and $D = 14.1$ cm. Figure 7 shows the modeled and actual interference patterns and their associated (log 10) spectral magnitude for the first 50 wavenumbers. The asymmetry in the actual interference pattern and associated shifts in the actual versus modeled spectral magnitude curves were due to differences between the ideal nature of the Fraunhofer model and the physical realization of the optical system. Imperfections in the optical source and minor variations in the slit widths contributed to deformations in the shape of the interference pattern. Fortunately, the key factor of interest in this experiment was not the precise shape of the interference pattern, but deviations in field strengths at the two slits and whether the DSM and phase at wavenumber 45 changed between the concentrate and relax conditions.

After determining optimal values for the physical configuration parameters, we used the nonlinear curve fitting routine to model the parameters associated with the light beam, namely A, B, x_0, and $y_{\max}$. The primary measurement of interest was the ratio A/B, because as this ratio shifts away from 1, either increasing or decreasing, the amount of interference decreases as indicated in Eq. (2) and illustrated in Fig. 8.

Figure 9 shows how the three intensities in Eq. (3) sum up to produce the observed interference pattern. Figure 9 (top) illustrates the case where $A = B = 1$, or $A/B = 1$. Note that because the optimized value for s_1 was slightly wider than s_2, the peak magnitude of the diffraction pattern shown in Fig. 9 (top), associated with s_1, was slightly larger than the pattern associated with s_2. Figure 9 (bottom) illustrates the case where $A = 1.5$ and $B = 0.5$ or $A/B = 3$. Notice that the maximum intensity associated with s_1 was over 3 times larger than the same value for s_2, and that interference declined.

2. Analyses

The best-fit values for parameters A, B, x_0, and $y_{\max}$ were determined for each interference pattern in each of the 12 selected test sessions. The modeled values we were specifically interested in were:

- A/B, the ratio of electric field intensity passing through the two slits, because the more this value shifted from 1, the more that interference would decline,

[2]The nonlinear curve fit routine was *lsqcurvefit*, from the MATLAB R2010a Optimization Toolbox, version 5.0.

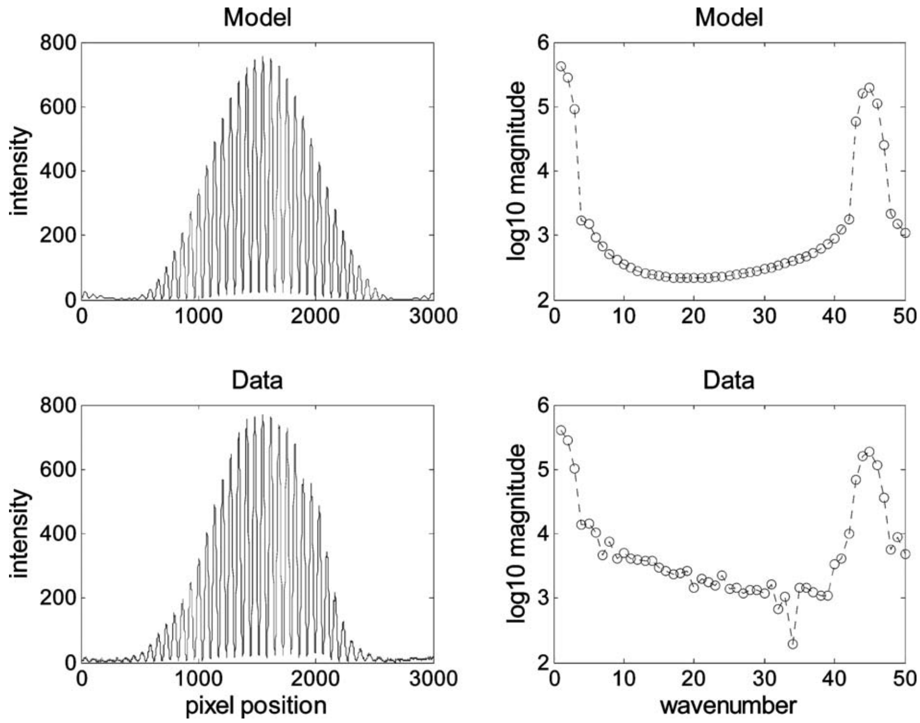

FIG. 7. Comparison of observed and modeled interference patterns and associated log spectral magnitude for first 50 wavenumbers. Note that the modeled value at wavenumber 45, which corresponds to the spectral power of the double-slit interference pattern, closely matches the value observed in the actual data.

- $A+B$, the total electric field strength passing through the slits, because this would reflect whether light was blocked by the psychophysical interaction process,
- x_0, the center point of the interference pattern, because this would indicate whether the beam's pointing direction had shifted, and
- $y_{\max}$, the maximum range of the interference pattern, because this would provide a secondary indication of whether the total illumination intensity had changed during the experiment.

We now calculated how much these parameters shifted as the C and R attention conditions alternated during the experiment. To eliminate possible bias in comparing these values due to signal drift over the course of a session, each estimated parameter was linearly detrended. Then, because directional shifts could not be predicted in advance (that is, which of the two slits might have been attenuated or blocked), the absolute value of the detrended data was employed.

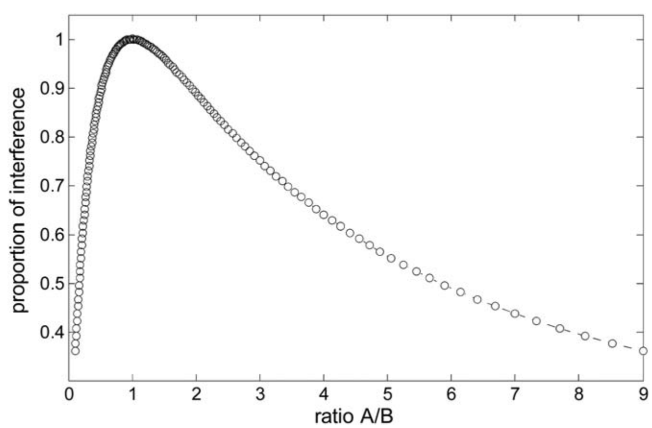

FIG. 8. Relationship between the ratio of electric field intensity passing through slit 1 versus slit 2, A/B, and the proportion of resulting interference (i.e., 1 is maximal interference, 0.5 is half the maximum interference).

To avoid parametric assumptions about the modeled data, a bootstrap technique was used to perform the statistical comparisons. It was applied to data from each session separately, resulting in one z score per session. The bootstrap procedure selected a random starting point in the data array, performed a circular right-shift, then compared the means of the two attention conditions using the originally recorded condition assignments and timing. This procedure was repeated 5000 times to build up a distribution of possible mean differences, and then the original mean difference $\bar{x}$ was compared with the distribution mean difference as $z=(\bar{x}-\mu)/\sigma$, where $\bar{x}$ was the mean and σ the standard deviation of the bootstrapped distribution. This procedure tested the data observed in the experiment against what could have happened if the test session had begun at different times. The circular shift technique was used to maintain the original sample sequence to take into account possible autocorrelations between successive samples. The resulting z scores per session were then combined across sessions using the Stouffer z method.

3. Results

Figure 10 shows that the absolute value of the (detrended) ratio A/B significantly increased in the concentration condition as compared with the relax condition. The deviation from chance at lag -3 s was associated with $z=4.38$, $es=1.26\pm0.29$, $p=0.00001$. The same modeling

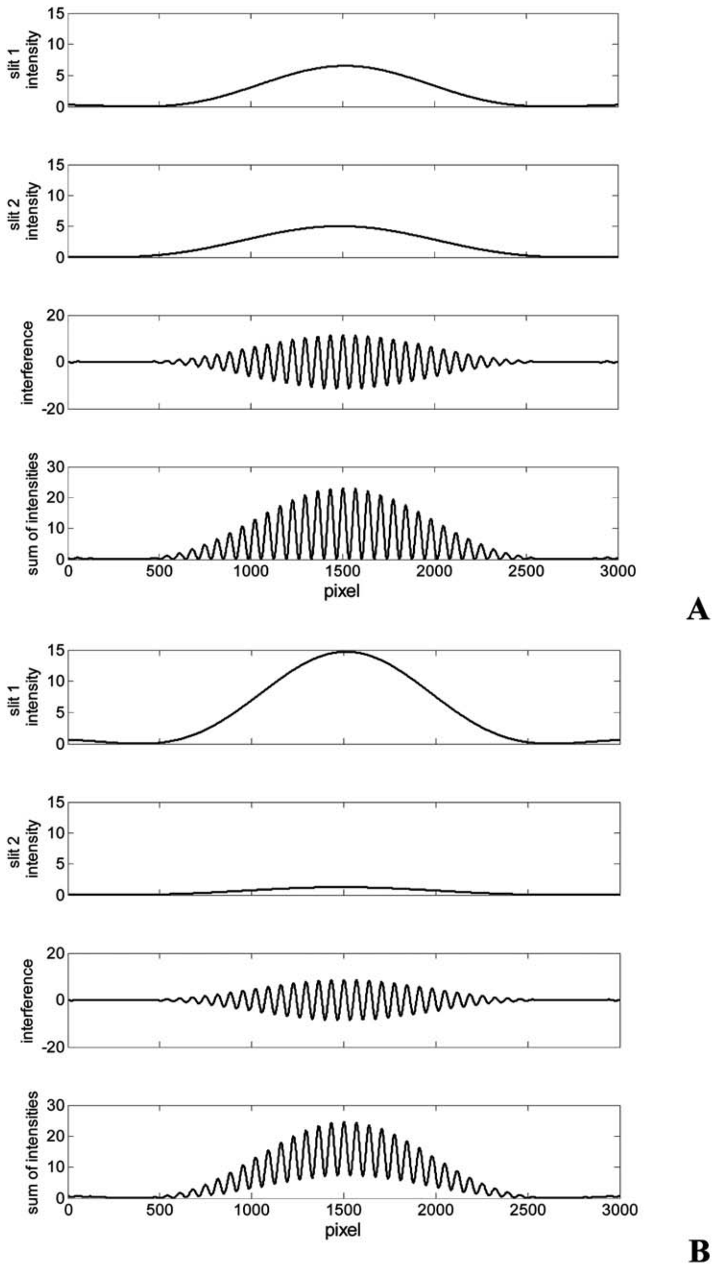

FIG. 9. (A) Illumination intensity resulting from each slit, interference between the slits, and the modeled interference pattern, when the electric field ratio $A/B = 1$. (B) The same measures when this ratio is unbalanced at $A/B = 3$.

effort applied to data from the control sessions (to test for analytical biases) showed virtually no change in A/B ($z = 0.022$, $p = 0.98$). Analysis of x_0 also showed a significant shift ($z = -3.88$, $es = -1.12 \pm 0.29$, $p = 0.0001$). The parameters $A + B$ and $y_{\max}$ did not show significant differences ($z = -1.26$, $p = 0.21$; $z = 1.23$, $p = 0.22$, respectively).

4. Interpretation

During the relax condition, participants were instructed to withdraw their attention from the optical system. During those periods, psychophysical interactions would be absent and photons passing through the system would be expected to behave in a wave-like manner (see Fig. 11). The ratio of the electric fields passing through the two slits would therefore indicate a relative balance, resulting in maximum interference, and the center point of the interference pattern would move as a weighted average of the centers of the two diffraction patterns. During the concentration condition, the photons would presumably be constrained by psychophysical interactions, so they would display more particle-like behavior. In the extreme case where photons acted solely like particles, they would only be able to pass through slit 1 or slit 2, but not both at once. Such dichotomous behavior would tend to unbalance the A/B ratio, which in turn would result in a decline in interference. This interpretation is speculative, of course, so at this early stage of investigation the primary value of the modeling effort is that it demonstrates a viable approach for analytically probing what would otherwise not be directly observable.

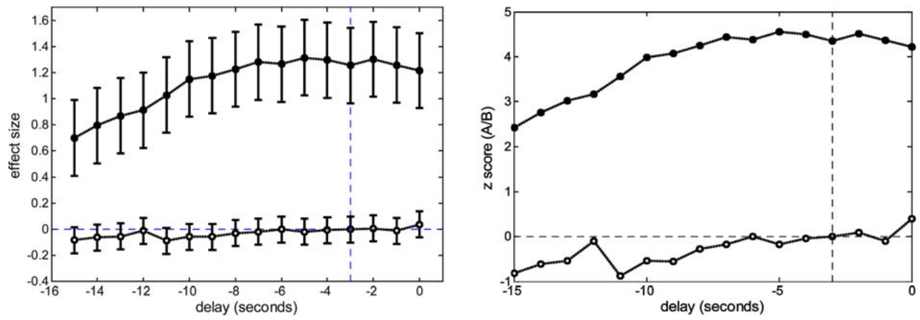

FIG. 10. (Color online) (Left) Effect size and one standard error bars for the absolute value of A/B for the subset of 12 significant experimental sessions (top line) and 100 control sessions (bottom line), lagged from 0 to -15 s. (Right) Same results expressed in the form of Stouffer z scores.

III. EXPERIMENT 2

To exclude the effects of potential heat and vibration artifacts caused by proximity between the human body and the optical apparatus, we conducted an experiment over the Internet to strictly isolate the optical system from the participants. The double-slit system used in this experiment was a duplicate of that used in Experiment 1, and the exact same preprocessing and statistical procedures employed in the first experiment were used to analyze the resulting data.

A. Method

In counterbalanced epochs, the participants—who could be located anywhere in the world—were instructed to shift their attention-toward or -away from the double-slit optical system located in our laboratory. Concentration epochs were 30 s in length, and relax epochs were 30 s plus 0–5 s in length, determined uniformly at random for each successive relax epoch.

1. Double-slit system and performance feedback

The distance from the slits to the camera in the optical system used in this test was approximately 16 cm. The HeNe laser and camera were powered on continuously throughout the experiment to avoid warm-up artifacts, and the optical system and experiment were controlled by a Microsoft Windows XP computer running a web server program written in MATLAB (version 2009 b). The server program accessed interference patterns from the camera at 16 frames per second and stored every fourth frame.

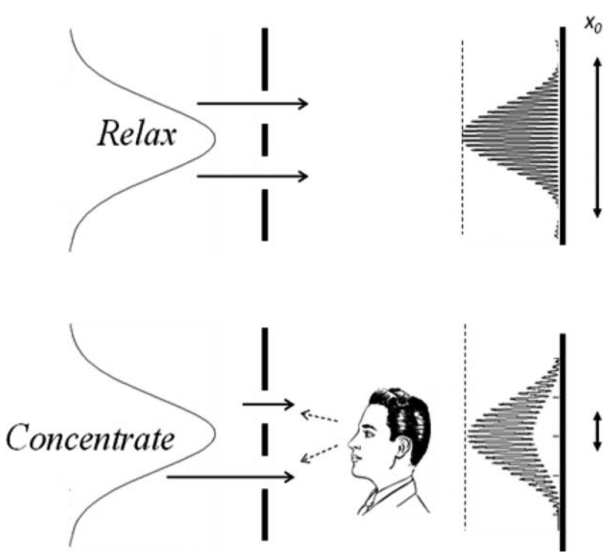

FIG. 11. Speculative interpretation of the results of the modeling effort. See text.

The program calculated the DSM from each interference pattern and used that value to provide performance feedback to the user during the concentrate epochs. This was accomplished by calculating the mean DSM recorded over each successive relax epoch, and comparing that value to a 3 s sliding window average of DSM measures observed during the following concentrate condition. No feedback was provided during relax epochs.

2. Internet client and data integrity

Participants performed the experiment through a client program embedded in a web page on a custom web site. The client received streaming data from the server and also provided graphic feedback. The application was written in Adobe Flash Professional and ActionScript (Versions CS5.5 and 3.0, respectively, Adobe Systems Inc., San Jose, CA). A survey associated with this experiment was hosted by www.SurveyMonkey.com (Palo Alto, CA), and the web portal to the experiment was hosted on a commercial hosting service. Standard web tools including Joomla! (www.joomla.org), PHP (www.php.net), and mySQL (www.mysql.com) were used to run the webpage, register users, and record online data. The experiment itself was controlled by a MATLAB program acting as a web server. Participant identities were protected by encrypting personal information with MD5, a commonly used 128-bit cryptographic hash function, and the web server provided protection against common server attacks, such as SQL code injection.

To further reduce the possibility that data from the double-slit system could be externally manipulated or falsely inserted into our database, the web server controlling the experiment did not accept data from external sources (with one exception, mentioned below). The data streamed to the user's browser by the web server were summarized performance feedback, whereas our web server stored the full camera images of the double-slit interference patterns in a location that was inaccessible to online users. All collected data were stored on our server and simultaneously uploaded to a cloud storage service. Copies of data on the server were also recorded on an external hard disk once a week.

To detect if a user began an experimental session but left in the middle of a session, or if their Internet connection spontaneously failed, at the end of each attention epoch the server waited for a handshake from the client computer. If the handshake (a predefined sequence of characters) did not occur within 5 s, then the test session was automatically closed and the server was reinitialized to wait for another user. While all test sessions were saved, only fully completed sessions were considered part of the formal database. Because the test streamed data live from the optical system located in our laboratory, only one person could take the test at any given time.

3. Participants

Participants were recruited by inviting people through social networks, blogs, and online newsletters. Over 13,000 people from 121 countries visited the test website between November 2011 and December 2012. About half of the users hailed from North America and a third from Europe. Approximately 1 in 10 persons who visited the web site signed up for the test, and about half of those completed the logon process and actually took the test. This low response rate was expected; the registration process was designed to reduce the number of frivolous users by requiring participants to fill out a demographic survey, to successfully complete a response challenge (www.captcha.net), and by requiring a real email address to complete the registration process.

4. Test procedure

To assist users in understanding the nature of the task, the registration website provided text descriptions and links to instructional videos. During a test session, performance feedback was provided in the form of a simple graph, where a line would go up if DSM was going in the predicted direction (i.e., decreasing), and vice versa. In addition, the pitch of a whistling wind sound followed the movement of the line; this allowed users to conduct the experiment with eyes closed. The computer also provided prerecorded voice instructions to announce the attention conditions with the phrases "now please concentrate" or "now please relax." There were 21 approximately 30 s epochs in a test run, so a typical test session lasted just over 11 min.

The demographic survey that each user filled out before taking the test asked for their name, gender, age, email, location, belief in ESP, and several similar psychological and personal belief questions. The ESP belief question was included because previous experiments have observed that openness to the possibility of ESP is often positively correlated with success in ESP tasks.[20]

5. Timing lags and other internet factors

Timing tests were conducted to compare when the web server sent a signal to the client to announce the attention instruction for each epoch, versus when data began to be displayed to the user. These tests indicated that the combination of (a) Internet data transmission delays, (b) human task-switching delays, (c) processing delays in our web server and the client's computer, and (d) environmental distractions, allowed us to estimate lags in the range of 5–10 s before a maximal effect was expected to occur.

Between November 2011 and January 2012, about 1000 online test sessions were contributed by about 500 people. We used those data as a pilot test to see whether the online experiment would successfully operate by itself, 24 h a day, and to assess our data integrity and network security schemes. Based on that experience, an improved system was developed that self-repaired after unexpected software crashes, and that automatically backed up all data to a cloud data service. Methods were also developed for preventing attempts to manipulate the data by malicious Internet software programs designed to penetrate or compromise web servers. Comparison checks on the data stored on the web server, on external hard drives, and on the cloud service gave no indications that any of the data in the formal experiment had been improperly accessed or corrupted.

To provide control data in this experiment, the web server was programmed to simulate a user by automatically conducting a test session at the beginning of each even hour, around the clock. These sessions were conducted the same way as human trials, including streaming live data to a distant Ubuntu Linux server programmed to simulate a human. The only difference between the experimental and control trials was that during control trials no one observed the data, and the incoming data stream was received by a Java client program instead of a web-based Flash client program.

6. Analysis

The same sequence of preprocessing steps described in Section II.A.5 was used to process the experimental and control data in this study, with one adjustment. The peak DSM in the first experiment was at wavenumber 45. The same peak for the optical system used in this experiment was at wavenumber 42, due to a different distance between the slits and the camera (16 cm versus 14 cm). So Step 4 in Section II.A.5 used wavenumber 42 instead of 45, and the range for detrending the middle of the spectrum was accordingly reduced by 3, i.e., from wavenumber 14 to 39 in the first experiment to 14 to 36 in this experiment.

B. Results

1. Users and sessions

The formal portion of the test was specified to run until a minimum of 2000 completed experimental and 2000 completed control sessions had been recorded. The formal test began in January 2012, and ten months later a total of 2240 experimental sessions had been contributed, of which 2089 were completed sessions. Those sessions were contributed by 685 people from 120 countries. During the same period, 2303 completed control sessions were also recorded.

According to the user survey, the participants ranged in age from 10 to 84 (mean age 42), 56% strongly believed that ESP exists and fewer than 1% strongly believed that it does not exist. Incidentally, the correlation between belief in ESP

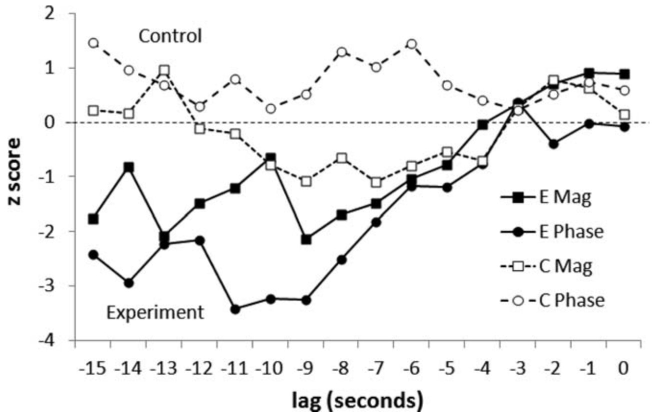

FIG. 12. Mann–Whitney *U*-test comparisons, expressed as *z* scores, for magnitude and phase at the spectral peak associated with the double-slit component of the interference pattern (wavenumber 42), calculated for data lagged from 0 to −15 s.

and meditation practice was $r = 0.23$ ($p = 3 \times 10^{-7}$), based on 451 people who answered both the ESP and the meditation question.

2. Spectral magnitude and phase results

Spectral magnitude and phase showed significant differential effects. The maximum deviation occurred at a lag of 9 s, falling within the expected range of 5–10 s. At a 9 s lag, the DSM significantly declined ($z = -2.63$, $es = -0.06 \pm 0.02$, $p = 0.009$), as did phase ($z = -4.175$, $es = -0.09 \pm 0.02$, $p = 0.00003$) (Fig. 12). By contrast, control data at that same lag did not significantly differ from chance for spectral magnitude ($z = -0.23$, $p = 0.81$) or phase ($z = -0.52$, $p = 0.60$). When considering the composite magnitude and phase analysis, for the experimental data at lag −9 s, the combined score is −4.31 ($es = -0.09 \pm 0.02, p = 2.6 \times 10^{-6}$), and for the control data the combined score is −0.51 ($p = 0.61$) (Fig. 13).

3. Effect of distance

Because this experiment was open to anyone with access to the Internet, we could test whether psychophysical interaction effects declined with increasing distance. To determine the approximate distance between each participant and our laboratory, we used data from MaxMind GeoIP (www.maxmind.com) and GeoNames (www.geonames.org) to determine the latitude, longitude, and time zone associated with each user's IP (Internet Protocol) address. From the latitude and longitude, distance was calculated as a straight line on the Earth's surface.[3] Time zone information was also used to determine the global geomagnetic field activity during a 3-h window in which each test session was conducted (as described below in Section V).

Distances ranged from 4 km to 18,000 km, with the nearest being a location close to our laboratory (Petaluma, California, USA) and the farthest being a location in South Africa. The next step was to determine an effect size for each experimental session; for this, we used a composite *z* score per session calculated at lag −9 s, as previously described. A linear regression was then formed between the composite *z* scores versus the distance in km for each participant, and the resulting slope and intercept were compared with the null hypothesis of zero.

For all online experimental sessions, the resulting slope was $(2.5 \pm 5.5) \times 10^{-6}$ *z*/km and the intercept was $z = -0.12 \pm 0.04$ (Fig. 14). This slope was not significantly different from zero ($z = 0.45$, $p = 0.65$), indicating no relationship due to distance, but the intercept was significantly negative ($z = -3.08$, $p = 0.002$), indicating that on average the session scores showed a decline in double-slit interference.

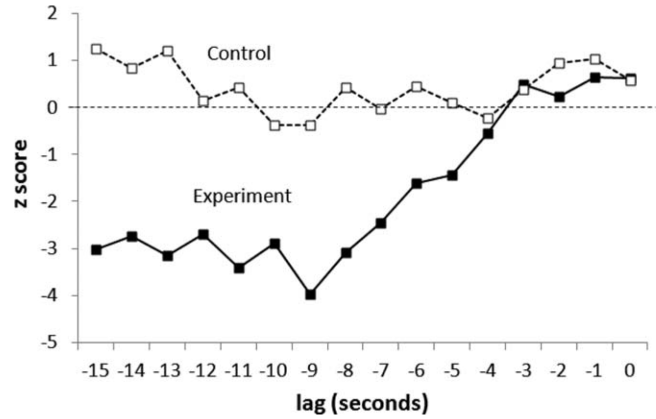

FIG. 13. Composite spectral magnitude and phase *z* scores for the online experimental and control sessions, lagged from 0 to −15 s.

4. Psychological and other performance modulators

The large number of participants in this experiment made it possible to analyze a number of psychological and environmental factors that might have modulated performance. Table I shows results for various partitions of the data, including speed of performance feedback (related to the speed of the participant's Internet connection), the state of the Earth's geomagnetic field (GMF) on the day and time of the test (which

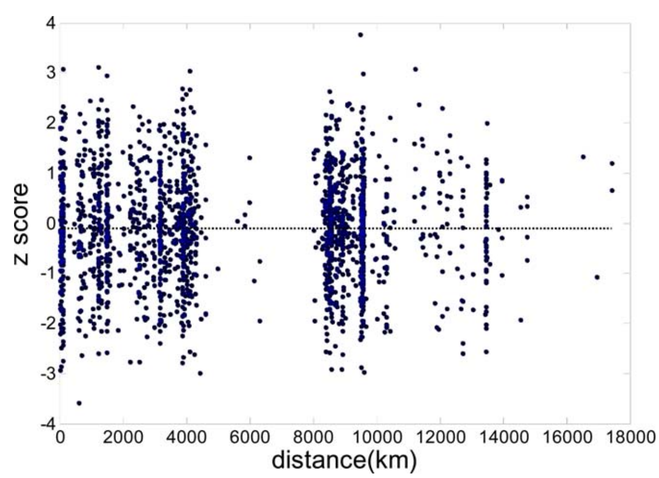

FIG. 14. (Color online) Composite *z* scores for all online experimental sessions, plotted by distance from the participant to the laboratory, and analyzed at lag −9 s. The dashed line is the slope.

[3]An Internet-savvy user might have accessed the experiment through a virtual private network, and thus the distance calculated for that user's location could potentially be inaccurate. However, we deemed it unlikely that this potential scenario would have introduced systematic biases into the present analysis.

TABLE I. Analysis of subsets of data for the online experiment at lag −9 s.

Data subset	Participants	Sessions	Overall z score (p)	Effect size (±se)	Intercept z (p)	Slope z (p)
All data	685	2089	−4.31***	−0.09 (0.02)	−3.39**	0.94
Faster internet connection[a]	438	1034	−5.25***	−0.16 (0.03)	−2.66*	1.49
Slower internet connection	430	1044	−0.98	−0.03 (0.03)	0.59	−2.03 *
High motivation[b]	34	796	−4.27***	−0.15 (0.04)	−0.50	−0.32
Low motivation	493	607	−0.53	−0.02 (0.04)	−1.15	−0.30
High meditation[c]	197	583	−2.32*	−0.10 (0.04)	−2.22*	1.46
Low meditation	297	828	−2.45*	−0.09 (0.04)	0.90	−2.21 *
ESP belief high[d]	391	1174	−2.90**	−0.09 (0.03)	−0.10	−1.45
ESP belief low	261	820	−2.75**	−0.10 (0.04)	−0.44	−0.54
Levitation belief high[e]	319	828	−3.39***	−0.12 (0.04)	−0.22	−0.94
Levitation belief low	246	902	−1.35	−0.05 (0.03)	−0.29	−1.09
GMF quiet[f]	441	952	−3.73***	−0.12 (0.03)	−0.26	−1.26
GMF stormy	375	979	−2.12*	−0.07 (0.03)	−0.52	−0.15

*$p < 0.05$ two-tailed;
**$p < 0.01$ two-tailed;
***$p < 0.001$ two-tailed.
[a]Based on the median number of samples recorded per session. Above, the median indicates a faster Internet connection.
[b]High motivation was indicated by participants contributing 10 or more sessions; low motivation by 1 or 2 sessions. Note: this particular outcome might also be due to optional-stopping behavior.
[c]High meditation experience is indicated by above the median response on a 7-point Lickert scale, ranging from a daily practice to no meditation experience at all.
[d]ESP belief was indicated on a 5-point scale, from certain to not at all. The distribution of responses was heavily skewed towards certainty, so low belief included anything other than a response of "certain."
[e]Belief in levitation was evenly distributed among responses on a 7-point scale, so high belief was indicated by a response above the median, and low belief below the median.
[f]A quiet Earth geomagnetic field was indicated by an *Ap* index during the three hour window of each session that was below the overall median *Ap* indices recording over all sessions; noisy GMF was above the median.

previous studies have indicated is a correlate of human performance in a wide range of human affairs, including in the present domain[16,21,22]), and the participant's motivation, meditation experience, belief in ESP, and belief in a more radical form of purported mind–matter interaction, levitation.

These analyses indicated that participants who received faster performance feedback achieved better results than those who received slower feedback (z(difference) $= -3.02$, $p = 0.003$, two-tailed), where the Internet connection speed was estimated by the number of data samples delivered by the web server over the course of the session. Slower Internet transmission rates delivered slower and more sporadic feedback.

The analysis also indicated that participants who were highly motivated, as indicated by those who provided 10 or more completed test sessions, performed better than those with lower motivation, as reflected by those who provided just one or two sessions (z(difference) $= -2.64$, $p = 0.008$, two-tailed). Sessions conducted on days with quieter geomagnetic fields, meaning geomagnetic *Ap* indices below the median value measured across all test sessions, produced slightly better results than sessions on noisy GMF days, and those who believed in levitation performed somewhat better than those who did not. By contrast, participants with an active meditation practice performed no differently than those with little or no meditation experience, and those who believed in ESP performed about the same as those who did not.

These analyses suggest that there may be many factors, from psychological to environmental, that modulate performance in the present task. Such factors are commonly observed in a wide array of cognitive tasks, suggesting that there may be optimal conditions that can be crafted, monitored, or otherwise exploited to enhance experimental yields. The analysis also indicates that the results in the present experiments are related to how humans actually perform attention-focusing and other real-world tasks,[23,24] thus providing a secondary indication that the results are not due to mundane physical or analytical artifacts.

IV. EXPERIMENT 3

This experiment was designed to simplify the data preprocessing and analytical procedures by using a more stable laser in a newly designed double-slit optical system. It also employed a task designed to help optimize participants' attention during the concentration epochs.

A. Method

1. Double-slit system

A beam from a 25 mW diode-pumped solid-state laser (642 ± 4 nm wavelength, single longitudinal mode, coherence length > 10 m, output noise $< 0.5\%$, TEM_{00}, pointing stability < 0.005 mrad/°C, temperature-stabilized, Model DL640-025-SO, Crystalaser, Reno, NV, USA) was passed through a clear quartz crystal, then a 1% transmission neutral density filter (Model NDL-25 S-2, Thorlabs, Newton, NJ, USA), and then through two slits with widths of 10 μm and separated by 200 μm (Lenox Laser, Glen Arm, MD, USA). The quartz crystal was used to expand the beam diameter from 1.1 mm to approximately 3 mm. The interference pattern was recorded by a 2048 pixel CCD line camera with a pixel size of 14×56 μm (14 μm pitch) and 12-bit A-D resolution (Model LC1100-USB, Thorlabs). The camera was located 18 cm from the slits, and the interference pattern was recorded by the camera approximately every 55 ms.

The optical apparatus was secured to an optical breadboard inside a heavy, optically sealed aluminum housing whose interior was entirely covered by mu metal (for magnetic shielding) and painted matte black. The experiment was controlled by a Microsoft Windows 7 computer running a program written in MATLAB (version 2009 b), and augmented by software libraries to interface the Thorlabs camera to the computer.

2. Participants and environment

All test and control sessions were conducted inside the previously described electromagnetically shielded chamber. Ten individuals recruited for the test were selected from a pool of participants known to maintain a meditation practice or other form of mental discipline requiring focused or creative imagination.

3. Procedure

Participants were invited to sit in a chair about 3 m from the optical system, they were given noise-cancelling headphones to wear, and they were invited to relax and listen to the instructions over the headphones. As in Experiment 1, participants were asked to not touch or approach the optical system at any time.

A recorded voice welcomed the participant and asked them to relax for 30 s while a presession baseline was recorded from the double-slit system. Then the voice announced, "When ready, press the button to begin the next trial." This allowed the participant to begin each trial whenever they felt ready to apply their attention to the task. This differed from the previous experiments, which presented timed instructions to concentrate or relax without regard to the participant's state of mental readiness.

When the button was pressed, the voice announced, "Please wait," 5 s later it said, "Get ready," and 10 s later it said, "Now please concentrate." Twenty-five seconds later the voice said, "Now please relax," and 5 s later the initial announcement was repeated, "When ready, press a button to begin the next trial." After 15 min, the voice thanked the participant and the session ended. Through this procedure, participants were able to initiate trials on demand. To be considered part of the formal database, only sessions with five or more trials contributed were used.

To assist participants in focusing on the double-slit system, real-time performance feedback was provided during the concentration epochs by varying the volume of a droning tone. The volume was controlled in near real-time by comparing the DSM value associated with the most recently recorded interference pattern against 50 most recent values recorded during the previous relax periods (with a *t*-test). The resulting *t*-score was transformed into an odds value which was constrained to fall between 1 and 100. That number was then used as a volume control, ranging from 1% (quietest) to 100% (loudest). When the double-slit spectral value declined the volume accordingly increased, and vice versa. To avoid abrupt changes, the volume values were averaged over 3 s. During relax and wait periods, the droning tone volume was set to zero.

4. Data preprocessing

Interference pattern data recorded during the experimental sessions were transformed by FFT into spectral magnitude and phase, but steps 4 and 5 described in Section II.A.5 were no longer necessary given the enhanced stability of the laser. Given the geometry of this double-slit apparatus, wavenumber 53 was associated with the peak spectral magnitude of the double-slit interference pattern.

5. Analysis

As before, mean spectral magnitude associated with the double-slit interference pattern was compared across all concentration versus relax epochs over the course of each test session. The same method was used when comparing mean phase. These means were accumulated for each of 20 planned sessions and evaluated using the previously described circular shift permutation technique. The outcome of each test session was expressed in terms of a magnitude plus phase composite z score, and those scores were combined into a single Stouffer z score across the 20 test sessions to provide the final statistic. Based on the results of previous experiments, we prespecified a lag of -3 s as the optimal time to evaluate the psychophysical hypothesis.

Unlike the previous experiments where attention conditions were automatically assigned on a timed basis, the present protocol required the participant to begin each trial at will. Thus, conducting a control session required a different approach. To do this, we ran 20 sessions without anyone present, then we assigned the trial-initiating button-pressing behavior recorded during each experimental session to a randomly selected control session, and then we analyzed the control data using the same analytical method that was applied to the original experimental data.

B. Results

Analysis of data from 20 test sessions contributed by 10 participants showed a modestly significant deviation in DSM and phase in alignment with the results of the first two tests. At the prespecified lag of -3 s, the composite z score was $z = -2.76$, $es = -0.62 \pm 0.22$, $p = 0.006$. Twenty control sessions conducted in the same environment and with the same equipment and analysis method resulted in a null effect with $z = 0.09$, $es = 0.02 \pm 0.22$, $p = 0.93$.

V. DISCUSSION

The experiments reported here are consistent with the results of previously reported studies using optical systems as targets in psychophysical experiments.[16,25,26] Together they suggest the existence of an attention-modulated mind–matter interaction effect. The combined outcome of the present three experiments, expressed in terms of an (unweighted) Stouffer z score, is

$$z = [(-5.16) + (-4.31) + (-2.33)]/\sqrt{3} = -6.81, p = 4.8 \times 10^{-12}.$$

Because of the unconventional nature of the hypothesized interaction, it is important to assess whether the observed outcomes might have been mimicked by one or more artifacts. Experiment 2 suggested that the results of Experiment 1 were probably not due to systematic fluctuations in heat, electromagnetic fields, or vibration caused by proximity of the human body. The results of Experiment 2 were supported by expected correlations between performance and psychological factors, including feedback rate, motivation, and attention task-switching delays. The lack of correlation with the factor of belief in ESP was unexpected, although the strong skew towards high belief in the participant population may have made that comparison unreliable. Evidence that the specific hardware implementations and experimental protocols used in Experiments 1 and 2 had not introduced artifacts was provided by the results of Experiment 3.

What the present experiments do not unambiguously demonstrate is that the observed effects are necessarily relevant to the QMP. That is, what we observed was a decline in interference correlated with periods of observation versus no-observation. This is consistent with a consciousness-related interpretation of the QMP, but there may be other ways of explaining these effects that do not require quantum concepts.

Another limitation in interpreting the results of these experiments is that in order to reduce noise due to signal drift and the multimodal output of the HeNe laser, data in the first two experiments required substantial preprocessing. Those transforms were applied uniformly to the data without regard to the attention conditions, so they could not have introduced biases in the comparisons of interest. However, the transforms do make it difficult to visualize what was happening physically within the optical apparatus. To address this problem, we were able to simplify the analytical approach in Experiment 3 by using a more stable optical system.

We may note that controlling the physical characteristics of this experiment was relatively easy as compared to controlling the psychological factors. For example, previous double-slit experiments suggested that meditators tended to outperform nonmeditators,[15,16] but Experiment 2 did not replicate that finding. In addition, belief in ESP did not appear to be as strong a predictor of success as previous research might have implied. Of course, the set and setting of controlled laboratory experiments are vastly different than unsupervised online tests, and those differences may have been sufficient to account for the lack of the expected correlations.

Finally, we recognize that the experiments reported in this paper are, by themselves, insufficient to definitively demonstrate the existence of a mind–matter interaction effect. To gain confidence in such a phenomenon would require scores of successful replications conducted in different laboratories. There is, of course, an existing literature reporting over a thousand conceptually similar studies conducted many over decades by dozens of independent laboratories.[14] From that larger perspective, the results reported here are not particularly surprising. However, theoretical models that adequately account for these effects have significantly lagged behind the empirical evidence, and until that problem is solved wider acceptance of this phenomenon will remain controversial. One of our goals in publishing this work is to bring this line of research to the attention of scientists interested in foundational problems of physics, and by doing so we hope to stimulate replications and discussions leading to testable theoretical models.

Future research on this topic would benefit by simultaneously studying personality, cognitive and neuroscience factors related to improved human performance in psychophysical tasks, by developing ever more sensitive physical targets, and by continuing to refine mathematical models that may help to shed light on the underlying mechanisms.

ACKNOWLEDGMENTS

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