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Psychophysical modulation of fringe visibility in a distant double-slit optical system

Dean Radin[1], Leena Michel[1], and Arnaud Delorme[2]

[1] Institute of Noetic Sciences, 625 Second St., Suite 200, Petaluma, California, 94952, USA

[2] University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0559, USA

Abstract: To investigate von Neumann's proposal that an "extra-physical process" is involved in the measurement of a quantum system, an online experiment was conducted using a double-slit optical system. In a counterbalanced fashion, participants focused their attention toward or away from a feedback signal linked in real-time to the double-slit component of an interference pattern. A line camera continuously recorded the interference pattern at 4 Hz, and for each camera image fringe visibility was determined for the central 20 fringes. During 2013 and 2014, a total of 1,479 people from 77 countries contributed 2,985 test sessions. Over the same period 5,738 sessions were run as controls by a computer programmed to simulate human participants. The results showed that with human observers the fringe visibility at the center of the interference pattern deviated from a null effect by 5.72 sigma ($p = 1.05 \times 10^{-8}$), with the direction of the deviation conforming to the observers' intentions. The same analysis applied to the control data resulted in an overall deviation of -0.17 sigma. After consideration of alternative explanations, these results were found to support von Neumann's conclusion that the mind of the observer is an inextricable part of the measurement process. This type of experiment offers a means of empirically resolving long-standing questions about the role of consciousness in the physical world.

Résumé: Pour examiner si le concept de von Neumann en mécanique quantique d'une interaction de nature « non-physique » est mieux interprétée comme une forme passive d'observation ou comme une influence active, une expérience a été menée sur Internet en utilisant un système optique à double fente. Dans un protocole contrebalancé, les participants ont concentré ou non leurs attentions sur un signal représentant en temps réel le niveau d'interférence du système de double fente. Une caméra enregistrait en continu le motif d'interférence à 4 Hz, et pour chaque image, la visibilité d'interférence des 20 franges d'interférence centrales a été calculée. Au cours des années 2013 et 2014, 1479 personnes en provenance de 77 pays ont contribué 2985 sessions. Au cours de la même période 5738 sessions contrôles ont été enregistrées par un ordinateur qui simulait un participant humain. Les résultats ont montré que la visibilité d'interférence pendant les périodes de concentration

diffère d'un effet nul avec une valeur de sigma de 5,60 par rapport aux périodes de non concentration ($p = 1,1 \times 10^{-8}$) avec une direction de l'effet qui est conforme à l'intention de l'observateur. La même analyse appliquée aux données de contrôle indique une déviation non significative de 0,04 sigma. Après examen des interprétations alternatives, les résultats observés ont été jugés comme étant en adéquation avec l'interprétation de Von Neurmann qui statue que la présence consciente de l'observateur est une partie inextricable de la mesure quantique. Cette expérience reproduit avec succès les résultats d'études précédentes et offre une solution empirique pour resoudre le rôle de la conscience humaine dans le monde sensible.

Keywords: quantum measurement problem; psychophysical interactions; double-slit interference

I. Introduction

> It is difficult for the matter-of-fact physicist to accept the view that the substratum of everything is of mental character. – Sir Arthur Eddington, in *The Nature of the Physical World*, 1928.

If the path that photons take through a double-slit interferometer is known by any means, then the photons will behave like particles, otherwise they will behave like waves.[1, 2] Numerous interpretations of this observational effect, associated with the "quantum measurement problem" (QMP), have been proposed. One of the earliest proposals, by John von Neumann, was based on characterization of the measurement process as a chain of interactions between physical entities – e.g., physical system, detector, eye, brain – with the process ending only when knowledge of the measurement is registered by what von Neumann called an "extra-physical" factor, i.e., an observer's mind.[3,p.419] As von Neumann put it,

> We must always divide the world into two parts, the one being the observed system, the other the observer. In the former, we [can] follow up all physical processes (in principle at least) arbitrarily precisely. In the latter, this is meaningless.[3, p.420]

The concept that the mind plays a role in quantum measurement was also seriously considered by Bohr, Schrödinger, Eddington, Jordan, Pauli, Planck, Jeans, Gödel, and London.[4, 5,6,7] In more recent times similar ideas have been discussed by Bohm, Wheeler, Wigner, Squires, Henry Stapp and Richard Henry.[6,8-14] While this line of thought has an impressive pedigree, today many physicists reject the idea of subjectivity in quantum measurement, relying instead on objective concepts like environmental decoherence.[7, 15]

Strong convictions can be found on all sides of the debate,[16] but among physicists and philosophers who specialize in the foundations of quantum theory, little consensus can be found.[5] This uncertainty, unresolved more than a century after Planck proposed the idea of a quantum, highlights the need for novel approaches to investigating the role of subjectivity in the QMP.

To do this, some have proposed to push the measurement boundary, also known as the "Heisenberg cut,"[17] all the way to the human eye.[18, 19] But the eye, and for that matter the brain, are physical entities; they are not "extra-physical." Thus, to take von Neumann's proposal seriously, it is necessary to use the human mind itself – consciousness – as the observer. Such an experiment was reported by Ibison and Jeffers.[20] They invited people to use "extrasensory perception" to gain which-path information from a double-slit optical system to see if von Neumann's extra-physical factor would affect the quantum wavefunction.[21, 22] Ibison's experiment was reportedly successful, Jeffers' was not.

In our version of this experiment, to operationalize the meaning of *observation* we invited people to simply direct their awareness toward or away from a distant, sealed double-slit optical system. To help focus their attention, a feedback signal was provided to each participant based on the amount of wave-like behavior in the interference pattern. The underlying assumption of this experimental design was that if, as von Neumann and others have proposed, consciousness is inextricably associated with the measurement process,[3] then the act of directing attention toward the optical system might be detectable via a shift in the double-slit component of the interference pattern.

In a series of 16 experiments using this approach we found that interference significantly deviated from a null effect during observation as compared to not observing.[23-26] One of those experiments was conducted over the Internet during the calendar year 2012; it was designed to be accessible at any time by anyone with Internet access. The experiment reported here was designed to replicate that study for two additional years, and due to a serendipitous error in programming the feedback signal (described later), the experiment also inadvertently provided a way to test whether the observational effect obtained in earlier experiments was due to a passive perceptual process or to an active steering or influence-like process, analogous to how suitably timed probes can produce either quantum Zeno or anti-Zeno effects (that is, how repeated observation can "freeze" or "accelerate" the evolution of a quantum system).[9, 27]

II. Method

A. Apparatus

As previously described,[25] the double-slit apparatus consisted of four components: (1) a 5 mW linearly polarized HeNe laser (Melles-Griot Model 25 LHP 151-249, 632.8 nm wavelength, 1 mm diameter, TEM_{00}, pointing stability < 0.03 mrad after a 15 minute warmup period, Melles-Griot, Albuquerque, NM, USA), (2) two 10% transmission neutral density filters (Rolyn Optics, Covina, CA), (3) a double-slit slide with slit widths of 10 microns and a separation of 200 microns (Lenox Laser, Glen Arm, MD, USA)[24, 25], and (4) a 3,000 pixel silicon CCD (charge coupled device) line camera with a pixel size of 7 x 200 microns and 12-bit A-D resolution (Thorlabs Model LC1-USB, Newton, NJ, USA). The camera was located 16 cm from the slits, and the line camera recorded the interference pattern by integrating light intensity for 40 milliseconds. The laser was powered by a Melles-Griot regulated power supply (rated at ±2% power drift per hour). The optical apparatus was housed inside a sealed aluminum housing painted matte black inside and out, and the laser and camera were powered on continuously. The entire setup was located near a web server in our laboratory.

The experiment was controlled by a Windows XP computer running a web server program written in Matlab (version 2009b, MathWorks, Natick, MA, USA) and augmented with software libraries used to interface the Thorlabs camera to the computer. The web server captured interference patterns from the camera at approximately 16 frames per second, and every fourth camera frame was recorded for offline analysis.

B. Procedure

The experiment was accessible by anyone, at any time, through a website (www.ionsresearch.com). To register for the test, each prospective participant was required to complete several steps to confirm that they were human. This included successful completion of a Captcha challenge (www.captcha.net), by filling out a questionnaire, and by providing an email address used by the web server to send a code number to complete the registration process. This multi-step procedure also helped to reduce the number of frivolous participants.

Validly registered participants were instructed by the web server to periodically shift their attention toward or away from the optical system. Attention-toward or *concentrate* epochs were 30 seconds in length. These were counterbalanced with attention-away or *relax* epochs, each of which was randomly assigned to last from 30 to 35 seconds in length. The purpose of the random timing was to decouple the attention epochs from potential periodicities that may have arisen in the interference pattern due to systematic fluctuations in the environment or to the laser's power output. Each test session consisted of a series of 21 alternating epochs, starting with relax, for a total session length of approximately 11 minutes.

C. Data integrity

The feedback signal streamed to participants' browsers was a summary statistic calculated on-the-fly by the web server. Raw data, consisting of line camera images recorded at 4 Hz, were never accessible to the participants. All raw data were stored on the web server and simultaneously uploaded to a cloud storage system. Data were also periodically offloaded to external hard-disks. No evidence of unauthorized access to the web server or cloud service was detected, and data stored on the server and the cloud were periodically compared and always found to be identical.

D. Feedback and web server design

To provide people with a way to indirectly observe the wave vs. particle-like behavior of the photons, during concentration epochs a simple line graph was continuously drawn on the participant's web browser's screen. No line was drawn during relax epochs. In the 2013 experiment, the direction the line moved was associated with the ratio of the peak spectral magnitude of the double- (D) and single-slit (S) components of the interference pattern, as determined by a Fourier transform. (This is illustrated and described in more detail in previous publications.[24, 25]) When the ratio D/S decreased, indicating a shift towards particle-like behavior, the line on the graph was programmed to move up, and vice versa. In addition, the pitch of a whistling wind tone followed the movement of the line, allowing participants to conduct the experiment with eyes closed. The line and the pitch were programmed to increase when the D/S ratio decreased because "up" is more commonly associated with better performance than "down."

In the 2014 experiment, the feedback variable was slightly changed but the intention was the same – the feedback value provided a way to associate a decrease in double-slit spectral magnitude with an increase in the feedback line and pitch. In both the 2013 and 2014 experiments, the participant's web browser provided voice instructions that announced the beginning of each epoch with the phrase, "now please concentrate," or "now you may relax." The program used to display this information was written in Adobe Flash Professional and ActionScript (Versions CS5.5 and 3.0, respectively, Adobe Systems Inc., San Jose, CA).

Due to a serendipitous coding error, the feedback used in 2014 accidentally reflected an *increase* in double-slit spectral magnitude. This mistake was not discovered until the 2014 data were analyzed. The error was traced to overlooking the difference between the conventional Cartesian coordinate system, where positive numbers are above the ordinate, versus the reversed coordinate system used in Flash, where positive numbers are below the ordinate. (The latter is a historical idiosyncrasy based on the top-to-bottom raster scan method used in cathode ray tube displays.)

To allow the web server to track the on-going status of each test session, at the end of each concentrate epoch the server waited for a handshake (a predefined sequence of characters) from the Flash client program in the participant's browser. If that handshake did not occur within 5 seconds, then the server assumed that the participant left the experiment's web page, and/or the Internet connection was interrupted, so it closed the session and reinitialized itself to wait for another participant.

All data from all test sessions were recorded. Because the experiment streamed the feedback signal live (in the form of a number from 1 to 100), only one person could take the test at any given time. If a participant attempted to use the system while it was being used by someone else, they received a message to wait a few minutes and try again. To assist participants in understanding the nature of the task, the registration website provided both text descriptions and links to instructional videos.

E. Timing lags

A time delay was expected before the hypothesized shift in fringe visibility would occur. The delay was due to several reasons: (1) Data streamed over the Internet are subject to data transmission limitations and buffering delays. (2) The signal provided as performance feedback during the concentrate epochs was based on a sliding window of the last 3 seconds of data, which was in turn compared to a baseline of the previous 30 seconds of data. This scheme was used to provide a smoothly moving feedback signal, otherwise it would have jumped about erratically as each new camera frame was recorded. (3) The alternating concentrate and relax instructions introduced about a 3-second cognitive “cost” due to the demands associated with periodically switching attention between tasks. (4) In each concentrate epoch the performance feedback began immediately but the spoken instruction “now please concentrate” took a few seconds to complete. And (5) unknown distractions at each participant’s location.

Based on these reasons, and also on the results obtained in a previous online study using the same basic design,[25] we predicted that the optimal deviation from chance would also occur in this experiment with a lag of +9 seconds. That is, a shift in fringe visibility would reach a maximum about 9 seconds after the web server switched the attention instructions from concentrate to relax, or vice versa.

F. Control sessions

To provide control data to test the equipment and analytical procedures, a computer running Ubuntu Linux was programmed in Java to simulate a human participant. This “robot” participant automatically initiated a test session with the experimental setup every hour on the hour, around the clock. Neither the web server nor the double-slit apparatus could tell if a human or a robot was on the receiving end of a given session, thus providing a rigorous way to test if human observation made a difference. If the Linux robot crashed the computer had to be rebooted manually, so on such occasions some scheduled control sessions were missed.

G. Analytical procedure

There were three sources of unavoidable noise in the optical system: pixel jitter in the line camera’s CCD (charge-coupled device), laser mode hopping, and ambient fluctuations in temperature. The first factor refers to electronic noise in the CCD chip, the second to spontaneous shifts of resonant frequencies in the HeNe laser, which can cause the laser’s power output to jump unpredictably, and the third to variations in room temperature which may in turn have influenced components in the interferometer.

To help avoid biases potentially introduced by these noise sources, fringe visibility (v) at camera frame *i* was used as the metric of interest, and defined as

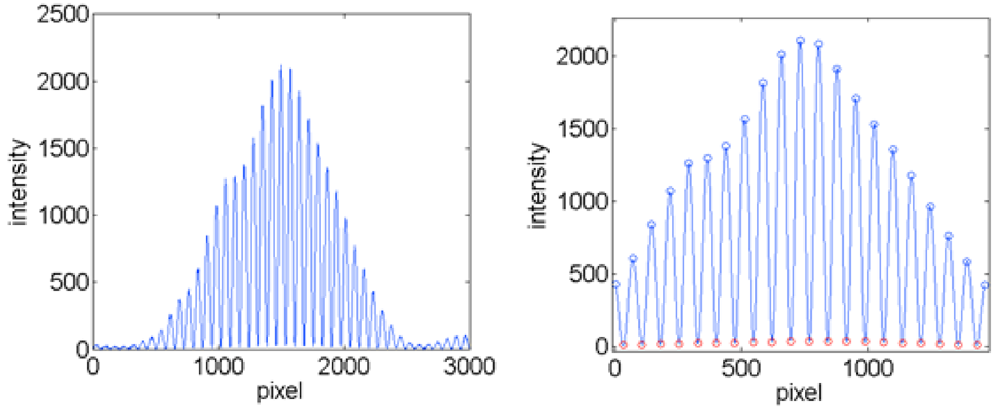
$$v = (I_{\max} - I_{\min}) / (I_{\max} + I_{\min}) \qquad \text{Eq. 1}$$

where I_{max} and I_{min} in Eq 1. refer to the illumination intensities of adjacent maxima and minima in interference pattern *i*. Fringe visibility is a useful metric because it provides a relative measure of interference, i.e. it takes into account fluctuations in overall illumination intensity, for example due to mode-hopping in the laser. Absolute measurements of interference do not take such variations into account.[a]

To measure v_i with greater precision, a second source of noise – pixel jitter – was mathematically reduced by smoothing the camera image. To do this a Savitzky–Golay local least-squares polynomial approximation was employed, 30 pixels in width (Fig. 1A).[28, 29] From the smoothed image the center segment of the interference pattern was extracted because that portion was expected to be most sensitive to changes in interference (Fig. 1B).

Next, the smoothed maxima and minima in the center of the segment were identified, resulting in multiple measures of fringe visibility per camera frame *i*, where each fringe measurement was calculated based on a minimum and the adjacent maximum to its immediate right. The ninth fringe from the left in Fig. 1B was our metric of principal interest because a previously published experiment using the same optical system and study design indicated that that fringe produced the most robust outcome.[25] For expediency that measurement is henceforth referred to as "fringe 9."

This procedure was then repeated for all camera frames recorded during each test session, which on average lasted about 11 minutes. Thus, in a completed session v_i was typically an array of about 630 seconds x 4 frames/second = 2,520 values. A second array recorded the attention conditions per camera frame, where "1" indicated concentrate and "2" indicated relax. These conditions were alternated in pairs, with relax followed by concentrate. Each test session was intentionally designed to be fairly short to ameliorate potential biasing effects of temperature and other environmental fluctuations, and also to encourage participants to complete full sessions.



A B

FIG. 1. (A) Smoothed interference pattern. The slight asymmetry in the interference pattern was due to minor misalignments in the optical apparatus. (B) Center segment, with minima and maxima identified. The y-axis is the level of illumination intensity returned by the Thorlabs camera.

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[a] An alternative formula for fringe visibility is $v \approx 1 - 2(I_{\min} / I_{\max})$.

Next, to provide a comparison of the difference in fringe visibility during the two attention conditions without relying on any parametric or distributional assumptions, the following resampling procedure was employed:

1) For each of *K* sessions, the attention condition array (i.e., concentrate vs. relax) was shifted +9 seconds due to the predicted time delay.
2) The median difference in fringe visibility in each session was determined, $\Delta v_k = (v_C - v_R)$, where *k* refers to a given session, v_C refers to the median of all fringe visibility measures recorded during concentrate epochs in that session, and v_R to the same during relax epochs. The term Δv_{99} refers to the median difference at fringe 9 lagged +9 seconds, as this was the center-most fringe at the timing lag expected to show the largest effect.
3) To avoid potential skewing effects of outliers and to provide a robust measurement of fringe visibility, the 10% largest and 10% smallest values of Δv_{99} across the *K* sessions were removed. The remaining number of sessions is referred to as K_o and the remaining median differences Δv_{o99}, with the *o* indicating outlier-removed. The effect of using other outlier rejection percentages will be addressed later.
4) Determine the grand mean of Δv_{o99} across all K_o sessions, call it $\overline{\Delta} v_{o99}$.
5) Randomly select K_o values from the set of Δv_o, with replacement. Determine the grand mean of these values; call it $\overline{\Delta} v_r$, where *r* indicates random selection.
6) Repeat the previous step 5,000 times to create a distribution of $\overline{\Delta} v_r$, then determine the standard deviation of that distribution, call it σ_r.
7) The null hypothesis predicts that $\overline{\Delta} v_{o99} = 0$. This is tested as $z = \overline{\Delta} v_{o99} / \sigma_r$.[b]
8) For exploratory purposes, we also performed steps 1-7 for each of the 20 fringes indicated in Fig. 1B.
9) To adjust the statistical results to take into account multiple comparisons (across the 20 fringes noted in step 8), we applied a procedure known as False Discovery Rate (FDR); this method takes into account positive correlations among the measures being compared (in this case, adjacent fringes).[30] Using the FDR adjustment, statistical significance is defined as *z* scores associated with adjusted probabilities of $p < 0.05$, two-tailed. All reported probabilities are two-tailed.

III. Results

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[b] Note that steps 6 and 7 were employed rather than using a simple counting procedure because if the deviation from the null is large it can become computationally intensive to determine the final *p* value. In the present case, analysis of the data showed that a counting procedure would have required millions of repeated bootstraps, thus a *z* score estimate was deemed a more efficient approach.

Over the course of 2013 and 2014, a total of 8,707 sessions were recorded (each with a minimum of 1,000 camera frames/session, as explained later), comprising a total of 140 GBytes of data. Of these sessions, 2,984 sessions were contributed by nearly 1,500 individuals from 77 countries, and 5,723 sessions were run automatically as controls. Most participants hailed from North America (68%), 18% were from Europe, and 14% were from elsewhere. The surface distance between participants and the interferometer ranged from about 4 km to 18,000 km, participants' ages ranged from 12 to 89 (average 43), and 50% of participants were female.

As shown in Fig. 2, analysis of the 2013 experimental data indicated that $\overline{\Delta}v_{o99}$ was 4.78 sigma (standard errors) below a null outcome (p = 8.87 × 10^{-7}, N = 1,308 sessions). When considering changes among all 20 fringes, 15 *decreased* significantly at $p < 0.05$ after adjustment for multiple comparisons. The 2014 experimental data indicated that $\overline{\Delta}v_{o99}$ was 3.41 sigma above the null (p = 6.45×10^{-4}, N = 1,676 sessions), and 8 of the 20 fringes *increased* significantly. Among control sessions, in 2013 $\overline{\Delta}v_{o99}$ decreased by 0.28 sigma (p = 0.78, N = 2,374 sessions), and in 2014 $\overline{\Delta}v_{o99}$ decreased by 0.10 sigma (p = 0.92, N = 3,349 sessions). None of the 20 control fringes tested in 2013 or 2014 were statistically significant after FDR adjustment for multiple comparisons.

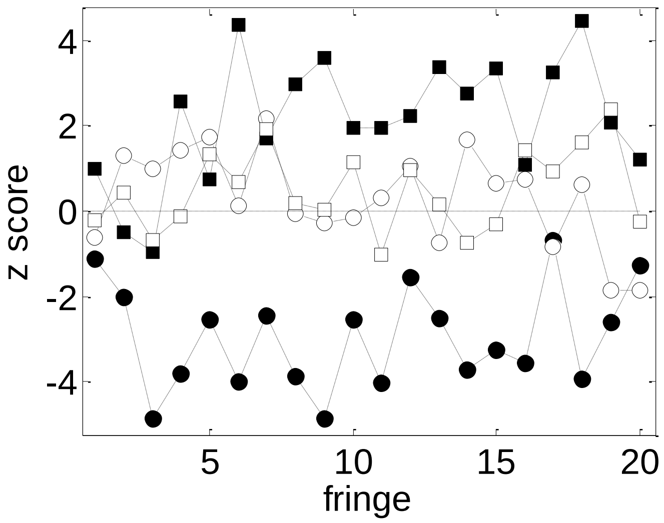

FIG. 2. Differential z scores associated with fringe visibility lagged +9 seconds for all experimental sessions in 2013 (black circles) and 2014 (black squares), and for all control sessions in 2013 (white circles) and 2014 (white squares).

Fig. 3 shows a histogram of $\overline{\Delta}v_{o99}$ for the 2013 and 2014 experimental sessions along with Gaussian curve fits. Because the number of experimental sessions differed across the two years, to provide comparable histograms the same number of sessions was used in each case (i.e., all 1,308 sessions from the 2013 database, and a randomly selected sample of 1,308 sessions from the 2014 database).

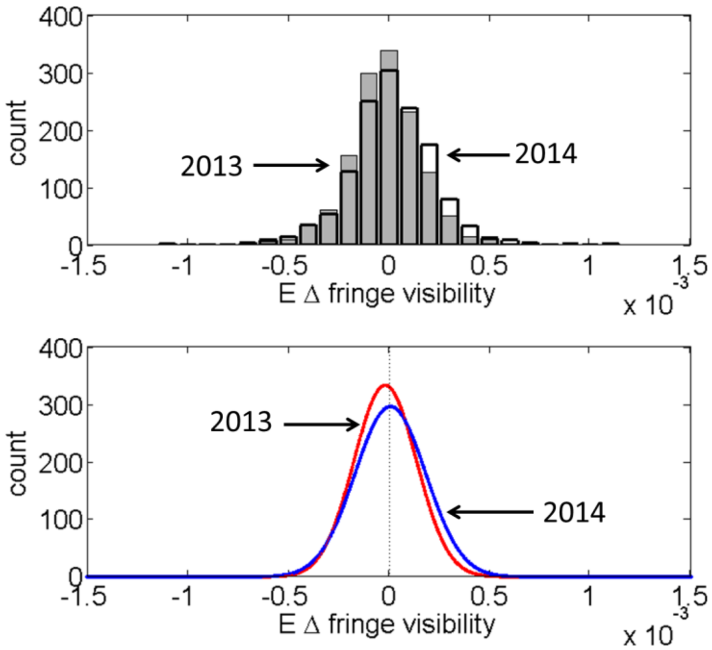

FIG. 3. (Top) Histogram of $\bar{\Delta}v_{o99}$ for experimental (E) sessions in 2013 and 2014, with 2013 data shown as grey bars and 2014 data as white bars with bold outlines. (Bottom) Gaussian fits to the histograms, showing a negative mean-shift for 2013 data and a positive mean-shift for 2014 data.

Fig. 4 shows the overall experimental results in terms of effect size (defined as $e = z / \sqrt{K}$) and one standard error bars ($s = 1/\sqrt{K}$, where K is the total number of sessions), for all data combined and with the sign of the 2014 data reversed for reasons discussed in Section 2.4. This analysis indicated that $\bar{\Delta}v_{o99}$ deviated from the null by a total of 5.72 sigma (p = 1.05×10^{-8}). The same analysis applied to all control data indicated that $\bar{\Delta}v_{o9}$ deviated by -0.17 sigma (p = 0.86). A total of 17 of 20 experimental fringes deviated significantly from a null outcome after adjustment for multiple testing; none of the 20 control fringes achieved statistical significance. Note that the phrase “all data combined” hereafter refers to combining the 2013 data with sign-reversed 2014 data.

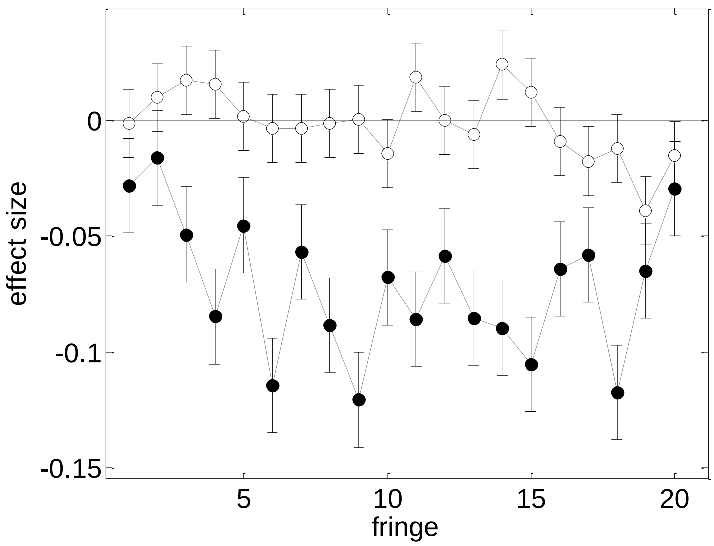

FIG. 4. Mean effect size and one standard error bars for the 20 fringes across all experimental sessions combined (black circles) and control sessions combined (white circles), time-lagged +9 seconds.

A. Time delays

To examine if these results replicated the previously reported time delay of +9 seconds,[25] the bootstrap analysis was repeated for all data combined but with time lags ranging from -20 to +20 seconds. As shown in Fig. 5, the maximum deviation was observed in the experimental data at +9 seconds; no corresponding delay was observed in the control data.

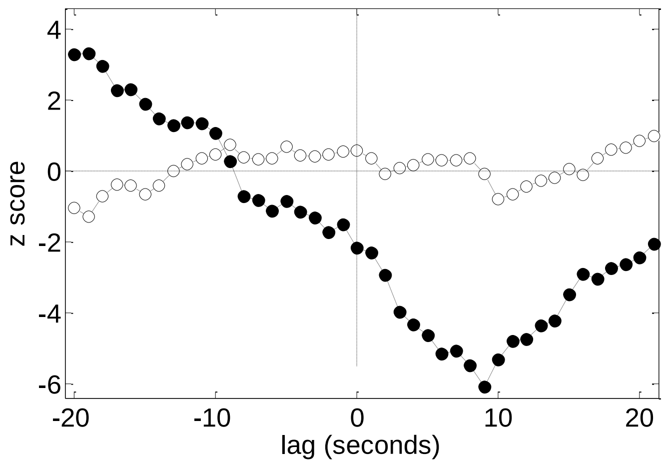

FIG. 5. *z* scores at fringe 9 for time lags ±20 seconds for all experimental data (black circles) and control sessions combined (white circles). The concentrate and relax epochs were counterbalanced and about 30 seconds in length. Lagging the condition assignments 30 seconds with respect to the data effectively reverses their meaning, i.e. data collected during concentrate epochs are now matched against data collected during relax epochs, and vice versa. Thus, the negative *z* score observed at +9 seconds should reverse at a lag of about -21 seconds, some 30 seconds away. The magnitude of the z score is not identical at +9 and -21 seconds because the relax epochs were not exactly 30 seconds long.

B. Optional stopping within sessions

Results presented to this point were based on sessions containing a minimum of 1,000 recorded camera frames. That included 96.3% of all experimental sessions (a total of 1,357 in 2013 and 1,742 in 2014) and 99.9% of all control sessions. The 1,000 frame threshold was used to select sessions completed approximately half-way, as such sessions were more likely to have been conducted with serious intent. But given that participants obtained near-real-time feedback about their performance, the possibility arises that if they were not performing well they might have been tempted to quit a session in progress. Likewise, completed sessions may have been more likely to occur when the observed outcomes were in alignment with the goal. If such biases occurred in a systematic way, then when considering all data combined, fringe visibility might have substantially decreased more as session lengths increased, i.e. optical stopping would manifest as a significant negative correlation between these two variables.

To investigate this possibility, all experimental sessions were examined that contained at least one completed relax and one concentrate epoch. Such sessions were at least 60 seconds long × 4 frames/second or 240 camera frames in length; there were a total of 3,016 such sessions. In contrast to the optional stopping prediction of a significant negative correlation between fringe visibility at fringe 9 vs. session length, the correlation was a nonsignificant $r = 0.0004$, $p = 0.98$. The same analysis applied to all control sessions was also a nonsignificant $r = -0.006$, $p = 0.64$. This indicates that the observed results were not due to optional stopping biases within sessions.

C. Optional stopping across sessions

Another form of possible optional stopping is related to the gambler's fallacy. That is, some participants may have obtained better results by chance, and as a result they kept contributing sessions as long as they continued to do well. If that behavior occurred in the present experiment then we might expect to observe an anti-correlation between the number of sessions contributed per participant and the effect size. Analysis of effect size by the number of sessions contributed showed that the correlation was not significant ($r = -0.09$, $p = 0.61$).

D. Outlier trim criterion

The outlier rejection criterion, step 3 in the analysis procedure outlined above, was set at a 10% trim. To study the impact of that threshold, the analysis was re-run using rejection criteria ranging from 0% to 50%, in steps of 2%.[c] The result is shown in Fig. 6, based on all data combined. It indicates that regardless of the outlier trim criterion, the experimental data deviated from chance whereas the control data consistently showed a null effect.

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[c] To trim the X% largest and X% smallest samples from a set of say N values, simply numerically sort all samples in the set and then remove the largest N * X% samples and smallest N * X% samples.

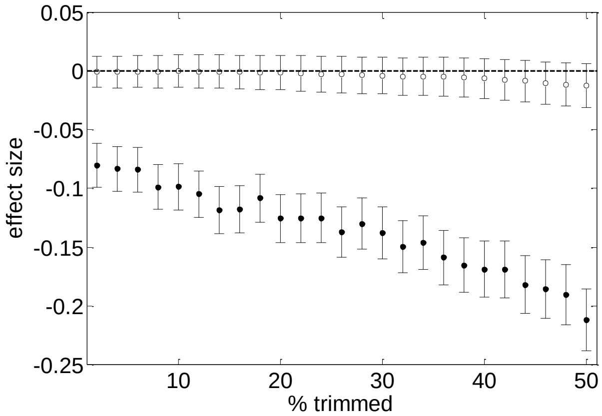

FIG. 6. Mean effect sizes and one standard error bars at fringe 9, lag +9 seconds, for all data combined; experimental results shown as black circles and controls as white circles. The x-axis indicates the percentage of outliers removed, from 0% to 50%.

E. Cumulative results

Could the outcome of this experiment have been due to a small number of participants who generated a few exceptionally deviant – and as such possibly spurious – sessions? To examine this question, the cumulative deviation of Δv_{o99} was examined in chronological order separately for 2013 and 2014 data. The result (Fig. 7) indicates clear trends in the experimental data, downwards in 2013 and upwards in 2014. No systematic trends were evident in the control data. This indicates that the experimental outcome was not due to a small number of deviant sessions.

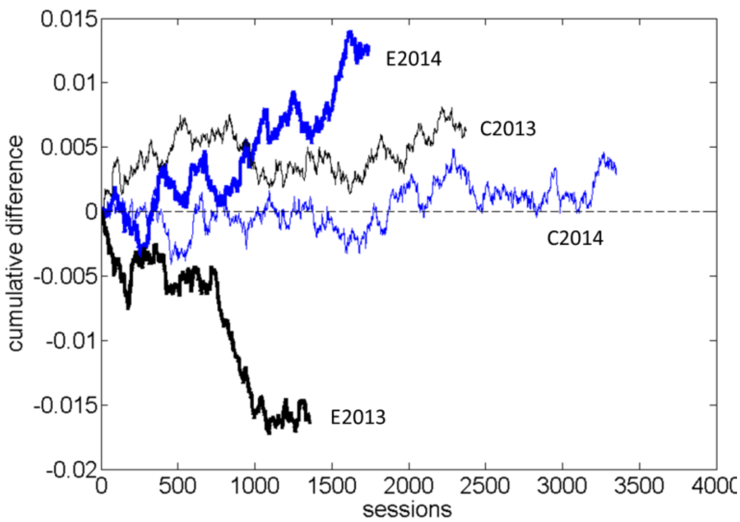

FIG. 7. Cumulative deviation of Δv_{o99} in 2013 and 2014 experimental (E) and control (C) data, each curve shown in chronological order.

F. Control sessions

Control sessions were intended to test the optical apparatus, computer hardware, software, and data analysis procedures for possible artifacts that might have led to spurious deviations.

Control (C) and experimental (E) sessions were thus designed to be as identical as possible. There were two aspects that could not be identical: One was that E sessions were conducted over the Internet with its varying data transmission rates, whereas C sessions were conducted through a local area network. This difference suggested that the inter-epoch handshake times in C sessions might have been slightly faster than in E sessions. That in turn could have led to a smaller number of samples recorded in C sessions. Another difference was that E and C sessions were necessarily conducted at different times given that all data were generated by the same optical system.

Because of these two unavoidable factors, to help judge how comparable the E and C sessions were, several analyses were performed. First, Δv_{o99} for each session (regardless of whether it was E or C) was examined in chronological order to study possible systematic sequential dependencies. An autocorrelation analysis showed no statistically significant dependencies through lag 500 (all correlations were $r < \pm 0.025$), indicating that the Δv_{o99} measures were effectively independent.

Next, to compare E and C sessions recorded under similar environmental conditions (ambient temperature, humidity, and vibration), each E session was matched by the closest-in-time C session, within a maximum time of one hour. For each time-matched session (k) the maximum illumination level (m) of each interference pattern was determined. Then the mean of those m values was determined per session ($\bar{m}_k$) and all such means were plotted in chronological order. Some 1,217 time-matched sessions were identified, and Fig. 8 (top) shows that $\bar{m}_k$ declined over the course of the experiment, probably due to a decrease in the laser's power output given that it was running continuously for several years.

While the maximum illumination level measured by the line camera dropped over 50% over the course of the experiment, Fig. 8 (middle) shows that the corresponding average in fringe visibility per session (at fringe 9) remained relatively stable, dropping only 0.6%. Of greatest importance, Fig. 8 (bottom) shows that Δv_{o99} exhibited essentially no drift.

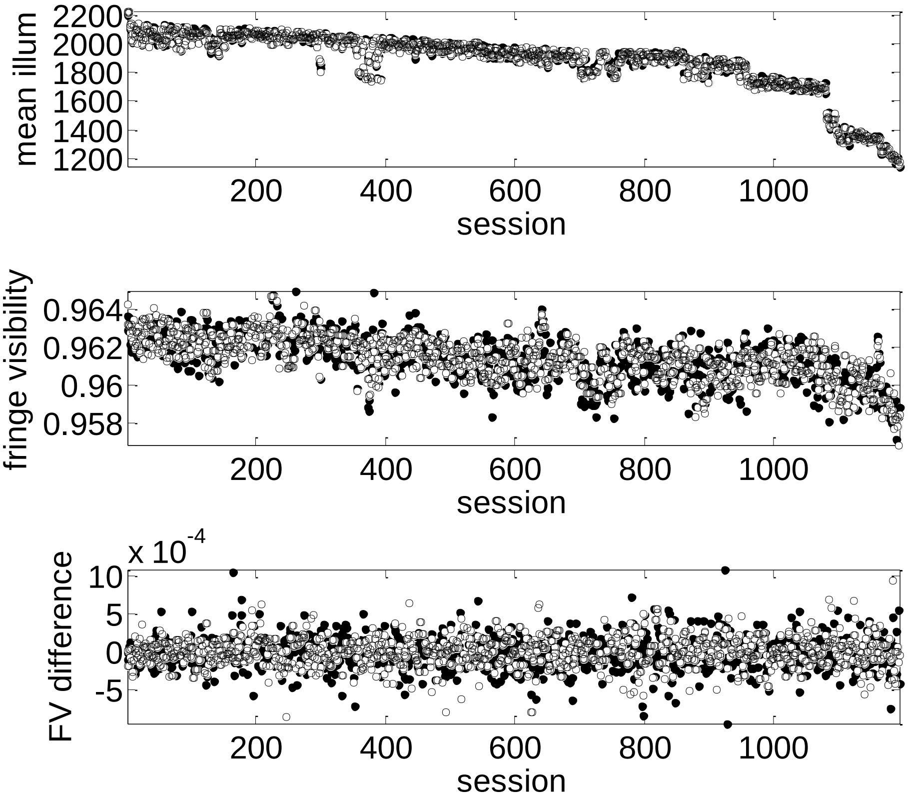

FIG. 8. (Top) Mean interference pattern illumination level, per session in chronological order. The y-axis is in terms of arbitrary units of illumination returned by the Thorlabs camera. Experimental sessions are shown as black dots, controls as white dots. (Middle) Mean fringe visibility, per session. (Bottom) Median difference in fringe visibility between concentrate and relax conditions, per session.

How comparable were the fringe visibility and illumination levels over the course of the experiment? Among the 1,217 time-matched sessions, the mean E fringe visibility was 96.139% and the mean C fringe visibility was 96.140%; this difference was not statistically significant (t = -0.17). The mean illumination level for matched E sessions was 1875.9, and for C sessions it was 1875.8; again this difference was not significant (t = 0.01). The same was the case for the number of mean samples in matched E and C sessions, 2493.0 and 2481.9, respectively (t = 1.49). As expected, due to slightly slower transmission speeds through the Internet, on average there were a few more samples in E sessions than in C sessions.

Despite the lack of significant differences in fringe visibility, interference illumination, and number of samples in matched E and C sessions, with regard to the metric of interest ($\overline{\Delta} v_{o99}$) E sessions deviated from a null effect (z_E = -4.59, $p = 4.43\times10^{-6}$) while C sessions were consistent with the null (z_C = 0.78, p = 0.43). Of greater importance, the effect size across the time-matched E sessions (es = -0.10 ± 0.03) was non-significantly different than the same measure across all recorded E sessions (es = -0.08 ± 0.02). This similarity in effect size offers additional evidence that the experimental results were unlikely to be caused by hardware, software, analytical or environmental artifacts.

G. Samples per session

A portion of the +9 second performance lag observed in the E data was assumed to be due to Internet transmission delays. To test this idea, $\bar{\Delta} v_{o99}$ was calculated for sessions with fewer than the bottom quartile of E samples/session (2,487 samples/session) and then again for sessions with more than the top quartile (2,548 samples/session). Sessions with fewer samples, reflecting longer inter-epoch handshake times, should – based on the aforementioned assumption – lead to longer performance lags, and vice versa. Analysis of the slower and faster sessions confirmed this prediction: For slower sessions the maximum deviation was observed at a lag of +10 seconds; for faster sessions it was observed at +5 seconds.

IV. Discussion

A. General

The present study, part of a growing body of supportive empirical evidence,[24-26, 31] is consistent with von Neumann's speculation that an extra-physical factor plays a role in the QMP. That said, these results do not support a *strong* role for the mind, as in consciousness literally causing a collapse of the quantum wavefunction.[32] Rather, a more modest function is suggested whereby the mind has the capacity to modulate probabilities associated with the transition from quantum to classical behavior. In terms of absolute magnitude these modulations are subtle. In the present experiment the percentage change in fringe visibility due to observation was on average about 0.001%. Still, it is important to not confuse the size of an effect with its theoretical importance.

It is instructive to examine how the interference minima and maxima contributed to produce the observed shift in fringe visibility. As shown in Fig. 9, for the 2013 data both the minima and the maxima increased (black and white stars, respectively), with the former increasing more than twice as much as the latter. This difference led to the observed *decrease* in fringe visibility. By contrast, for the 2014 data, the minima decreased and the maxima increased (black and white diamonds, respectively), leading to the observed *increase* in fringe visibility.

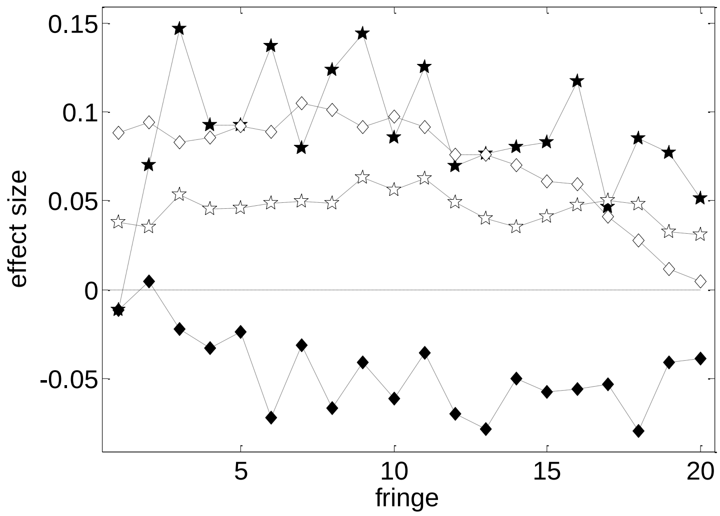

FIG. 9. Effect size for shifts in fringe minima (black stars for 2013 data, black diamonds for 2014 data), and for shifts in fringe maxima (white stars for 2013 data, white diamonds for 2014 data).

The direction of the shifts observed in the 2013 data was not surprising, because nearly any interaction with an interferometer would be expected to decrease fringe visibility. However, the shifts observed in 2014 *were* unexpected because an increase in fringe visibility is less likely to occur spontaneously. That is, given that fringe visibility was already about 96% on average, the system had less "room to move." While the precise mechanisms underlying this observational steering effect remains poorly understood, the present results suggest that von Neumann's psychophysical interaction may be better interpreted as an active rather than a passive form of observation.[33]

B. Toward a mechanism and additional empirical support

The outcome of this experiment may be surprising to some, but it is important to note that von Neumann's interpretation of the QMP does not require any alteration to the mathematics of orthodox quantum theory. This experiment only presents a challenge to commonly held *assumptions* about the role of consciousness in physical reality. Many scientists prefer a monistic view of reality,[34] and yet von Neumann's proposal and the outcome of this experiment suggest a form of dualism. While discussion of philosophical preferences is beyond the scope of this article, it is worth mentioning a proposal offered by Pradhan, who noted that of the dozen or more various interpretations of the QMP only one (Cramer's transactional interpretation[35]) addresses the possible meaning of the conjugate wave function $\Psi^*(r,t) = <\Psi \mid r,t>$.[36, 37] Pradhan proposed that if the real function Ψ is considered the physical aspect of the wavefunction, and the complex conjugate Ψ^* the mental aspect, then the results of the present experiment can be explained in straightforward terms. Such a proposal would require a tweak to the Born Rule because Ψ^* would now be viewed as an active process that includes mental intentions and goals, whereas Ψ would remain a passive mechanistic process.[38]

Beyond consideration of possible mechanisms, from a purely empirical perspective the present results are in alignment with an extant literature that spans nearly a century.[21] One of the better known classes of relevant studies has involved intentional influence of truly random number generators (RNG) where the underlying randomness is based on quantum events.[31, 39, 40] A theoretical model proposed to account for successful RNG studies is known as "Observational Theory." It was described by Houtkooper as:

> The measurement problem in quantum mechanics can be used to hypothesize an observer who adds information at the collapse of the wave function. For each random event one of the possible outcomes becomes realized as the event is being observed. The basic tenet of observational theory is: the statistics of single events become biased if the observer is motivated and prefers one of the possible outcomes over the other.[41, p.171]

C. Future research

Successful experiments using optical systems as targets of psychophysical interaction, involving Fabry-Perot,[42], Michelson,[23], and Young double-slit interferometers, have been reported by four different principal investigators from three laboratories.[20, 24, 25] The results of these studies are consistent with von Neumann's proposal, but that interpretation may be more explicitly explored by, e.g., manipulating the goal of the experiment by linking the feedback to different desired outcomes. In such experiments, participants could obtain feedback that appeared to have the same goal, like mentally intending a line drawn on a graph to go upwards. However, they should not know the precise association between the feedback signal and the physical aspects of the apparatus used to derive that signal. If in such experiments the output of the optical system conformed to the goal defined by the feedback signal, rather than to the act of observation alone, then that would provide additional support for an active influence that causes specific physical outcomes to manifest.

D. Replication attempts

For those interested in replicating these studies, we recommend that this type of experiment should not be regarded as a conventional physics experiment, nor as a conventional psychology experiment. It is instead an amalgam of both disciplines, and as we have discussed in previous publications sensitivity to both domains is therefore essential.[24, 25] On the physical side the optical system should of course be as stable and as noise-free as possible, and on the psychological side the means by which participants are asked to interact with the system should be as simple as possible, but not so simple as to induce boredom. To further optimize the experimental yield, we suggest that the first phase of the study be devoted to finding individuals who appear to have talent in this task, and then formal tests conducted only with those individuals. As a rough estimate, about one in a hundred candidates selected at random may be expected to exhibit some talent. To help optimize the participant selection process, we have found that the ability to maintain stable attention is a key factor, and thus on average experienced meditators tend to perform better than those who have not had any attention training.

Because of the controversial nature of this type of experiment, the credibility of the results might further benefit by having investigators participate who hold different *a priori* expectations, including those who are favorably inclined toward a consciousness-related interpretation and those who are skeptical. However, effort should be taken to create a supportive testing environment for both investigators and participants, while at the same time ensuring that data collection is rigorously controlled and monitored. In addition, it would be useful to pre-register the planned analysis in an online repository.

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