

Title: Can the conscious observer affect the collapse of the wavefunction?

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Abstract:

Background

Radin and colleagues have found that human attention and intention seems to affect quantum processes at the most basic level. Several other researchers have found similar results. These results, if true, would have significant implications regarding the fundamental nature of consciousness and its role in quantum processes.

Aims

We aimed to replicate and extend Radin et al.'s findings. In two experiments we aimed for direct replications, in one experiment we investigated the possible underpinning of Radin et al.'s findings. Moreover, in one of our replication attempts we measured EEG to possibly correlate psychophysical influences with neural activity.

Method

In Experiments 1 and 3 subjects received direct feedback on the variance in luminance of an interference pattern produced by a 2-slit set-up. In Experiment 3 EEG was measured. In both experiments the subjects were instructed to increase the variance. In Experiment 2 entangled photons were either directed at a camera, or at the head of the participant. Subjects performed a 2-back task, or a listened to a guided meditation.

Results

None of the experiments yielded reliably significant results. However, in Experiment 1, where we tested a relatively large number of experienced meditators (unlike in Experiment 3), results trended in the expected direction. Moreover, if we only included participants who subjectively felt that they could affect the interference pattern, then we replicated the findings of Radin et al.

Conclusions

The results of our experiments are inconclusive. Although we did not replicate the findings of Radin and colleagues, we did uncover some results that seem to support their claims. We aim to conduct more rigorous replication attempts in the future.

Published work resulting from the project supported with the present grant separated in abstracts (proceedings and meetings), full papers and contributions included in books:

None

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Introduction

In this research we aimed to replicate and extend the findings of Radin and colleagues regarding the impact of human consciousness on the interference pattern observed when light self-interferes (Radin et al., 2012, 2013, 2016; Radin & Delorme, 2022). In a nutshell, across several experiments Radin and colleagues found evidence that human intention, and human attention, seems to alter certain aspects of the interference pattern produced by photons. We focused on the notion that the mean luminances of the interference pattern remain the same, but the variance of the luminance changes due to human intention/attention.

We believe that the findings reported by Radin and colleagues are important for several reasons. First, not only Radin, but several other researchers (Bösch et al., 2006; Dunne et al., 1989; Jahn et al., 2007; Radin et al., 2006; Schmidt, 1973, 1974; Tressoldi et al., 2014) have reported findings that suggest that humans can affect quantum processes that should be entirely random. So, there is good reason to believe that the claimed effects may be real. Second, if the claimed effects are real, then this could dramatically impact our understanding of fundamental quantum processes. For instance, the measurement problem (Jauch, 1964; Schlosshauer, 2004; Wigner, 1963) is at the heart of quantum physics. Unobserved quantum processes are entirely deterministic, governed by the Schrödinger wave equation. However, whenever a measurement is performed, then an indeterministic ‘collapse of the wavefunction’ occurs. The Schrödinger wave equation now turns out to be a probability distribution, which only translates into an actuality upon measurement. Naturally, this raises the question of what is special about measurements. Why do these collapses never occur spontaneously, and only when quantum processes are measured. What even counts as a measurement? One intriguing explanation of the measurement problem is the von Neumann-Wigner interpretation (Chalmers & McQueen, 2021; London et al., 1939; Neumann, 1955; Wigner, 1967) which states that it is the consciousness of the observer that collapses the wavefunction. After all, according to quantum physics all interactions between ordinary matter (electrons, protons and neutrons) are completely governed by the deterministic Schrödinger equation. Quantum physics does not place any limit on the reach of the Schrödinger equation. It supposedly governs the behavior of 10 particles as much as it governs the behavior of 10^{30} particles. So, just adding more ordinary matter should never result in the rise of any indeterminism – even if these particles together constitute an object like a measurement device. Thus, the only entity present at each measurement that could possibly consist of anything else than ordinary matter – and could therefore cause an indeterministic collapse of the wavefunction – is the human mind. Consequently, according to the von Neumann-Wigner, or “consciousness collapses”, hypothesis, quantum physics implies that the wavefunction collapses at the last possible moment during a measurement, i.e. when it reaches human consciousness.

In short, the idea of the consciousness collapses hypothesis is that when a particle is unobserved it is completely governed by the deterministic Schrödinger wave equation. E.g. if a photon encounters a two-slit set-up it splits in two probability waves that pass along both possible paths. In other words, the photon enters a superposition state. This is still completely deterministic – given the set-up of the experiment this superposition will inevitably follow. Subsequently, the photon interacts with a measurement device, which also enters a superposition (a superposition of indicating that the photon has taken path A and path B). Again, this superposition deterministically follows from the previous events. Subsequently, a signal from the measurement device goes to the human eye (or another human sense organ). This still causes no indeterminism. Effectively, the retina is an unconscious measurement device, which will also enter a superposition. Only when the signal

reaches the neural correlates of consciousness, the superposition indeterministically ‘collapses’ into an actuality.

Interestingly, the great challenge of the ‘consciousness collapses’ hypothesis is not theoretically. After all, in our view at least, the hypothesis follows straightforwardly from the assumptions of quantum physics. Moreover, not only does quantum theory assert that ‘spontaneous collapse’ does not occur when more particles are involved, recent empirical findings (Kovachy et al., 2015; O’Connell et al., 2010) support this assertion. Given that collapse does eventually happen, this logically implies that it must be caused by something that is different from ordinary matter, yet that is present at every measurement. Here it indeed seems that the human mind is the prime candidate. E.g. a camera certainly does just consist of ordinary matter.

However, the great challenge for the ‘consciousness collapses’ hypothesis is how it can be tested. E.g. the claim of ‘consciousness collapses’ is that macroscopic objects, like cameras, can be in a superposition. Yet, this assertion can not be tested by simply looking whether a camera is ever in a superposition. After all, by looking at the camera, a conscious visual experience emerges, which collapses the superposition of the camera. Thus, although the camera is supposedly in a superposition before one looks, one can never observe this superposition directly.

Radin et al.’s findings provide an interesting way out of this conundrum. These findings suggest that not only does consciousness collapse the wavefunction, it also does so in a non-standard way under certain circumstances. This conjunction of hypotheses *can* be empirically investigated. Note that if Radin et al.’s results are reliably replicated, then this provides support for two assertions – i) consciousness collapses the wavefunction, ii) it does so in an unusual way if humans direct their attention/intention to quantum processes. However, in contrast, if Radin et al.’s findings turn out to be unreliable then this could be due to either one of the assertions being false. That is, replication of Radin et al.’s findings supports the notion that consciousness collapses the wavefunction. Yet, failure of a replication does not directly refute the consciousness collapses hypothesis.

In sum, Radin et al.’s findings can have a huge impact on our understanding of the link between human consciousness and quantum processes. This, in turn, would be pivotal for our understanding of the (fundamental) nature of consciousness. Moreover, several researchers have reported similar findings as Radin and colleagues. Therefore, we believe that rigorous attempts to replicate Radin’s results are appropriate.

Methods and Results

We performed three experiments. In Experiments 1 and 3 we aimed to replicate findings reported by Radin et al. In Experiment 2 we employed entangled photons to find any psychophysical effects. Experiment 2 was substantially different from the original Radin et al. experiments, since there was a physical interaction between the entangled photons and the brain – although there was no direct physical interaction between the measured photons and the human brain. Moreover, in Experiment 3 we measured EEG while subjects performed the task. We did so to establish whether neural activity, as measured by EEG, correlated with any psychophysical interactions. In the following we will describe the experiments and the measured outcomes in more detail. To preview, we did not replicate the original findings of Radin and colleagues. Moreover, we did split-half analyses which yielded a nearly significant finding in the first experiment. This finding was not replicated in the third experiment (although the results did trend in the same direction). Crucially, this ‘nearly significant’ effect was in line with earlier finding reported by Radin and colleagues (increased variation in the luminance of the interference pattern due to the presence of a human observer). In Experiment two

we again performed a split-half analysis, followed by confirmatory tests. However, this did not yield any significant findings. Moreover, the correlation with neural signals measured by EEG did not produce any reliably significant effects either. In sum, the experiments we conducted have not led to conclusive findings. Although we did not exactly replicate Radin et al.'s findings, there were certainly some results that may seem to support the claims of Radin and colleagues. This is especially true given that we only managed to test ~30 people, of which a substantial part were *not* trained meditators. We aim to continue this line of research, since it may be that with increased power we do replicate Radin et al.'s findings.

Experiment 1: increasing variance in the interference pattern

Set-up and subjects

In this experiment we created an interference pattern by shooting infrared light, through two slits, at a camera. For this we used a LP785-SAV50 infrared laser (which we purchased at Thorlabs inc.). The laser was set at its lowest output of 10 milliAmpere. The interference pattern was measured by a DCC1240M camera, also purchased at Thorlabs inc. The set-up of laser, two-slits and camera was positioned at a honeycomb breadboard (B60120A, purchased at Thorlabs) for stability.

The experiment was as follows. 30 minutes before the start of the experiment the laser was switched on at 10 milli-Ampere. This was done so that the output of the laser was stabilized. Subsequently, for 10 minutes a baseline measurement of variance was performed. The interference pattern consisted of light and dark bands. Per band we first measured the average intensity (by averaging the signal across five minutes of recorded images). Subsequently, the average variation, per band, was measured (i.e. taking the absolute difference between the average intensity (per 200 milliseconds) and the measured intensity for the last 200 milliseconds) for five minutes. This average variation was averaged across all bands to obtain one number for the average variation in intensity, for each 200 milliseconds of recording, across the entire interference pattern.

The subject was situated in the same room as where the set-up on the breadboard was placed. The subject had no direct contact with the set-up and was situated approximately 3 meters away from the set-up. The task of the subject was as follows. The subject performed 8 blocks of approximately 7 minutes. There were two possible orders, either the subject performed 'intention blocks' during blocks 1,3,6 and 8, and 'relax' blocks during blocks 2,4,5 and 7, or vice versa. During the intention blocks the task of the subject was to try and increase the variance of the signal. The subject received direct feedback on whether variance was increased or decreased, compared to the pre-recorded baseline, by seeing a score and a bar that went up or down. The bar was green if the score was above 0 and red if the score was below 0. At the end of the block the subject saw her average score (a score between -100 and +100). A positive score indicated that the variance was higher than during the baseline measurement, and the larger the score the higher the variance. The participant was instructed to try to increase the variance as much as possible. After the entire experiment the subject indicated whether she thought whether she could consciously affect her score. During the relax blocks the subject saw no feedback and only saw the text 'relax and do nothing' on the screen. The subject was instructed that during this time she could do anything, including closing her eyes and drifting off.

The entire experiment lasted approximately one hour. We tested 17 subjects. Twelve of the subjects were experienced meditators and/or highly interested in parapsychology. The other five subjects were students from the University of Amsterdam or the University of Leiden. This experiment, and experiments 2 and 3, were ethically approved by the University of Amsterdam (FMG-8725).

As a control, before or after testing each subject, we ran the experiment without a human subject present. Our main aim was to replicate the finding, of Radin and colleagues, that variance increased when humans attended to the two-slit setup, compared to when they relaxed. Additionally we performed exploratory tests on half of the data which we subsequently tested on the other half of the data.

Results

Our main analysis focused on the difference between 'intention' and 'relax' blocks. The dependent measure was whether variance was increased during 200 milliseconds intervals, across the different bands of the interference pattern. We defined the variable 'score' as follows. The baseline variance was subtracted from the measured variance during the last 200 milliseconds. This was divided by the baseline variance. E.g, if the measured variance was 5.1 and the baseline variance was 3, then the score was $(5-3.1)/3.1$, i.e. 0.613. Subsequently this number was multiplied by 5 to yield the final score.

Figure 1 depicts the average scores in the intention and the relax blocks. Figure 2 depicts the average scores in these blocks in the control experiment where no human was present.

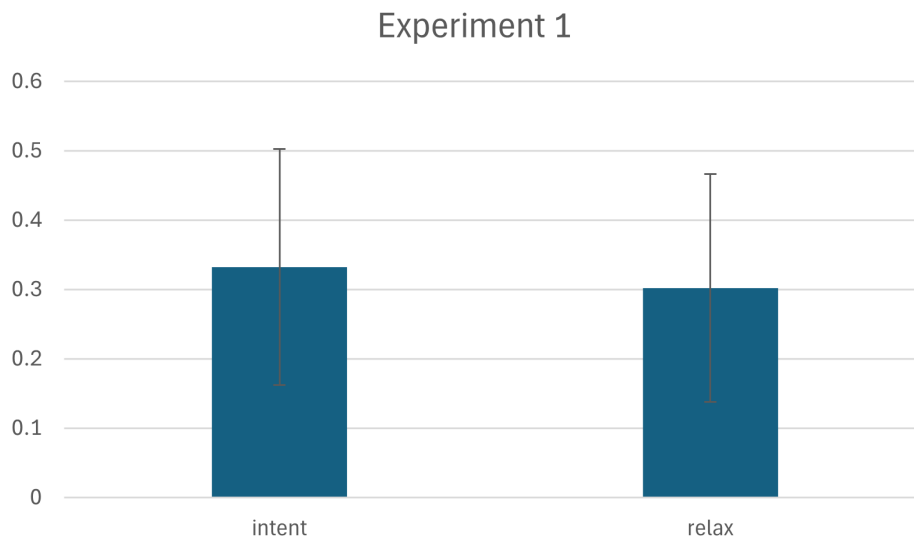


Figure 1 Variance of luminance across the interference pattern across both the intention and relax blocks. Zero indicates that there is no difference between variance during the experiment and the baseline measurement before the experiment. A positive score indicates an increase in variance, a negative score a decrease in variance.

Control Experiment

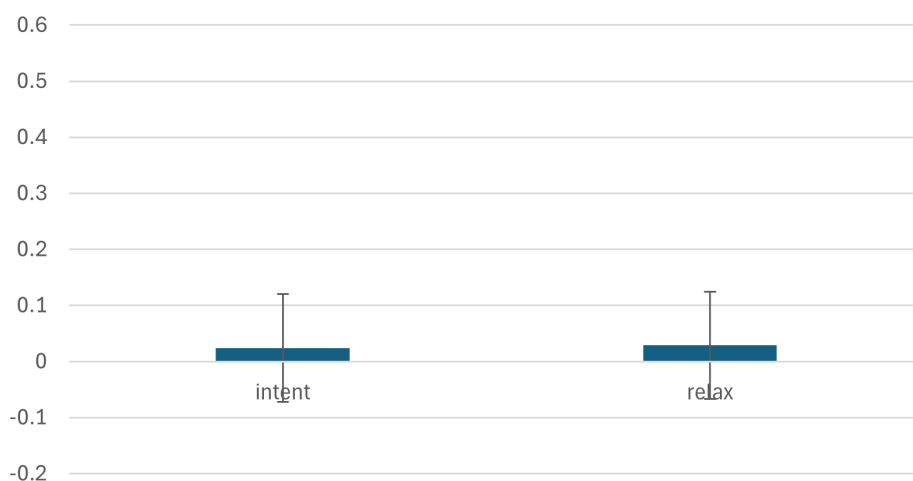


Figure 2 The same variance of luminance across the interference pattern in both blocks in the control experiment. In the control experiment no human was present.

In the control experiment, we measured no difference between the intention and relax blocks (scores in both blocks were 0.02 and 0.03 respectively, $p = .85$). Crucially, in Experiment 1 we measured no significant difference between variance score in the intention and relax blocks either (scores were 0.33 and 0.3 respectively, $p=.49$).

The exploratory analysis of one half of our data yielded two hypotheses for further testing. The first hypothesis concerned the average luminance in the troughs (i.e. the bands with minimal luminance in the interference pattern). Our initial analyses on one half of the data suggested that average luminance in the troughs was increased in the intention versus the relax blocks. However, in the second half of the data this hypothesis was not confirmed ($p=.76$). Our second hypothesis was that although variance was not different across blocks, it was increased compared to baseline. This hypothesis was somewhat confirmed (one-sided t-test, $p=.037$). However, if we apply a Bonferonni correction to our tests (because we performed three confirmatory tests), then alpha should be .017, implying that the result was not significant.

Finally, 10 out of 17 participants indicated that they had the feeling that they could affect the variance of the interference pattern. If we restrict our analysis to these 10 participants, then we find that in the intention blocks an average score of 0.65 is achieved, and in the relax blocks an average score of 0.56 occurs. This difference is statistically significant ($p=.03$). Moreover, the difference with the intention blocks and the baseline score of 0 is significant as well ($p=.003$). The same analysis for the 7 participants who indicated to have the subjective impression of having no impact yielded a score for the intention blocks of -0.125 and for the relax blocks of -0.06. The difference in the variance score between the blocks was not significant ($p=.44$), nor the difference between score in the intention blocks and the baseline of 0 ($p=.65$). Although it is intriguing that some subjects indicated that they felt that they could affect the interference pattern, and this is confirmed by statistical analyses, we should be careful to not read too much into these findings. After all, the participants received feedback about their score during the intention blocks. So it can simply be that if the variance happened to be high during the intention blocks, subjects falsely believed that they caused this.

In sum, our findings did not replicate the findings of Radin and colleagues. However, it is unclear whether this should count as a complete failure of replication. First, we only tested 17 participants, due to logistical challenges. This is a much lower amount of participants than we aimed for, and then reported by Radin and colleagues. Second, especially when we compare our results to the baseline condition where no human was present, our data did trend in the expected direction. Variance of luminance across the interference pattern seemed to increase when a subject was present. However, whether this subject tried to increase variance, or just relaxed, seemed not to have a huge impact. Third, Radin et al. measured an increase in variance, but they did not give feedback on this variance. In fact, in their tasks subjects received feedback on whether they succeeded in shifting the mean of the peak of the interference pattern. We speculate that this may have given a clearer target for the subject. Thus, in retrospect, we should have perhaps provided other feedback than we actually did. Unfortunately we did not realize this before Experiment 3. Future replication attempts will employ different feedback.

Experiment 2: Influencing entangled photons

Set-up and subjects

Sixteen of the seventeen subjects that participated in Experiment 1 also participated in Experiment 2 (only one experienced meditator did not participate in Experiment 2). The second experiment deviated significantly from the first experiment. In this experiment there were four blocks. During two blocks (1 and 3 for half of the participants, 2 and 4 for the other half) the participants had to perform an auditory two-back task with letters. The subjects listened to auditory input consisting of a stream of letters. If the current letter was the same as two letters back, then they had to say the letter out loud. In the two other blocks participants listened to a guided meditation. Moreover, either during the first two, or the last two blocks (for half of the participants the first two blocks, for the other half the last two blocks), infrared (810 nanometer) entangled photons were shot at the head of the participant. This was light at a very low intensity (approximately 10 kilohertz). In the other two blocks these photons were blocked before they reached the head of the participant.

The set-up was as follows. First, we constructed a source of position-momentum entangled photons. Since this cannot be acquired, we had to build this source ourselves. We did so by collaborating with the quantum optics lab of Wolfgang Loefler of the University of Leiden. We again employed a honeyboard breadboard from Thorlabs to install our set-up (to prevent motion artefacts). Moreover, the set-up used a 405 nm 100 mW laser, aimed (via mirrors) at a BBO type-0 crystal. These crystals were acquired via Topag inc. This produced an output of 20 kHz of 810 nm photons. This ring of photons was momentum entangled. We employed a knife-edge mirror to split this ring in half. Half of this ring went to the head of the subject on half of the blocks (as described earlier). The other half of the photons was measured by an iXon EMCCD camera (Ganesh et al., 2020) – which should be capable of reliably detecting single photons – which we rented from Andor. This camera produced an image every 100 milliseconds. We recorded during the entire block, which lasted approximately 7 minutes, yielding 4000 images per block. The room in which the subjects were situated was completely darkened, to the extent that we measured nearly no photons at all in the room. Moreover, we build a box around the entire set-up to i) prevent light from entering the set-up, ii) prevent laser light (especially the potentially harmful blue laser light) from exiting the set-up. The subject was situated next to the box. This box contained a square of approximately 10 by 10 centimeters that could either be open or closed. If the square was opened, then half of the entangled photons would hit the head of the subject approximately at the temple.

Results

We used the first 1000 images per block to generate hypotheses, which we tested on the second 1000 images per block. We only compared the conditions where entangled photons hit the head (which should cause entanglement with neural matter) to the condition where the entangled photons did not hit the head. In the first 1000 images of the ‘entangled’ versus the first 1000 images of the ‘not-entangled’ condition we tried out several measures of average luminance and variance of luminance at different locations of the half ring of entangled photons. This led to seven possible candidates that could produce a significant difference between the entangled and non-entangled conditions. Respectively, these were the average luminance of the peaks on the half ring, the difference between the luminance of the peaks and the adjacent 2 pixels on the same row, the average luminance at the border of the half ring, the variance in the luminance of the peaks, the variance in the difference between the luminance of the peaks and the adjacent pixels, the variance in the luminance at the border and the difference in luminance between 2 pixels on both sides of the border (which were either just outside, or just inside the ring). In all cases a positive score means that the luminance, variance or difference is higher in the entangled than the non-entangled condition. Figure 3 depicts the findings of the confirmatory analyses. The x-axis depicts the different measurements as outlined earlier, the y-axis depicts the average difference in photons. So, for example, the peaks on the half ring were, on average, 0.41 photons brighter in the entangled than the non-entangled condition.

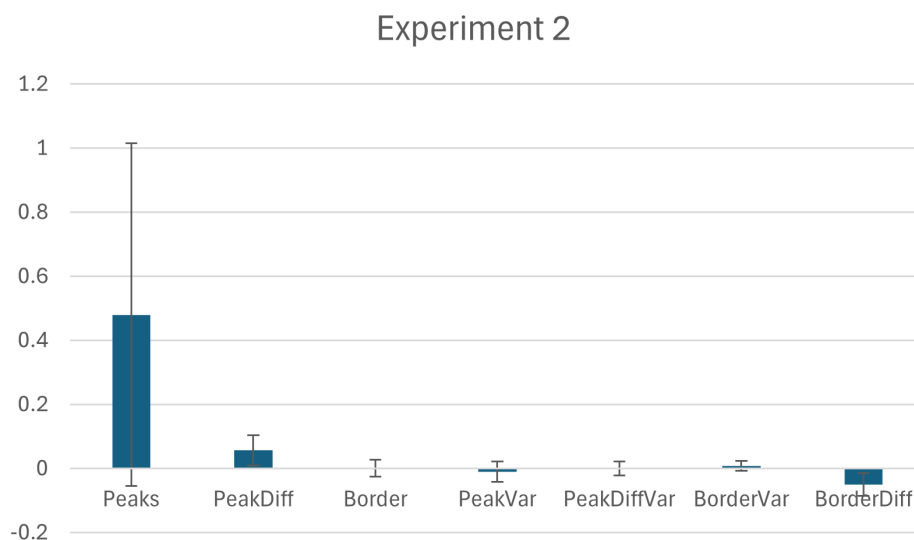


Figure 3 A depiction of various measures comparing the impact of entanglement of photons with neural matter. Across all measures the differences between the two conditions were small (less than one photon in all cases). Moreover, none of the differences reached significance.

As can be seen from Figure 3, most differences turned out to be small. Yet, the error bars were minimal as well, indicating very little variance in all dependent measures. For instance, the “Border Difference” only differed by an average of -0.05 photons across both conditions. Yet, this yielded $p=.21$ – clearly far from significant, yet a remarkably low p-value given the magnitude of the difference.

Overall however, we again failed to find any significant results (all $p>.2$). The motivation for Experiment 2 was based on our own theory. We speculated that the findings of Radin and colleagues were perhaps due to spontaneous entanglement of the photons causing an interference pattern and neural matter of the subjects. We like to point out that this is *not* a speculation that was put forward by Radin and colleagues. Crucially, despite the challenging nature of this experiment, and the very

high precision we achieved (the EMCCD camera seems to have produced extremely precise measurements), we did not find any results approaching significance. In fact, the results of Experiment 1 had at least one finding that approached significance (difference in average variance across the interference pattern depending on the presence of a subject), yet Experiment 2 did not come close to this. Thus, the findings of Experiment 2 suggest that spontaneous entanglement does not play a major role in the findings of Radin and colleagues.

Experiment 3: Correlating increasing variance in the interference pattern with EEG signals

Set-up and subjects

Experiment 3 was identical to Experiment 1 except for the following changes. In addition to measuring the interference pattern, we employed EEG to monitor neural activity. The EEG equipment was rented from the company Psyphy (<https://psyphy.io/>), who also assisted in data-analysis of the EEG signal. We focused on three EEG bands, Alpha, Beta and Gamma, and pre-planned to correlate activity in these EEG bands with performance in the intention blocks.

In Experiment 3 we tested eleven participants. Because our recruitment efforts among experienced meditators were unsuccessful, these participants were recruited among students of the University of Amsterdam. None of the participants in Experiments 1 and 2 participated in Experiment 3. Moreover, we did not ask afterwards whether participants had the subjective impression that they successfully affected the interference pattern.

Results

Based on the outcomes of Experiment 1 we performed two confirmatory analyses. First, we compared the score indicating the level of luminance variance in the interference pattern between the intention and relax blocks. Second, we compared the average in the blocks where humans were present to a baseline score of 0. Moreover, we investigated three EEG correlations. All correlations were with the score in the intention blocks. These scores were correlated with Alpha, Beta or Gamma activity respectively. Figure 4 depicts the behavioral results.

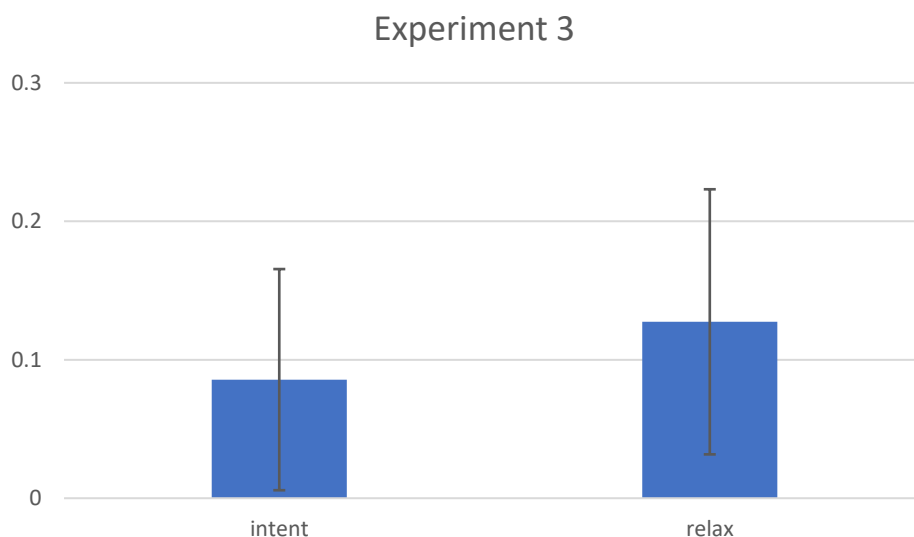


Figure 4 Overview of the results of Experiment 3. The variance scores in this experiment were numerically lower than in Experiment 1. Moreover, the difference between the intention and relax blocks ran in the different direction than we expected.

The results in this Experiment were markedly different from the results in Experiment 1. First, the variance scores were *lower* in the intention than in the relax blocks (0.09 versus 0.13), although this difference was not significant ($p=.11$). Moreover, although the variance scores, across blocks, were again higher than the baseline score of 0, this difference was not significant either ($p=.25$).

For the EEG activity, we correlated average Alpha, Beta and Gamma activity with variance scores in the intention condition. This yielded Pearson R 's of -0.49, -0.5 and -0.25 for Alpha, Beta and Gamma respectively. The associated p -values are $p=.076$ (Alpha), $p=.07$ (Beta) and $p=.24$ (Gamma). So, none of these effects reached significance, especially if we take into consideration that α is 0.01 in this experiment because we conducted five confirmatory tests.

Discussion

Across three experiments we obtained mixed results. For instance, in Experiment 1, if we only selected participants who thought that they could influence the interference pattern, then we indeed replicated Radin et al.'s findings. However, if we consider the variety of tests we performed, then we did not find any reliably replicable effect.

However, before drawing strong conclusions based on our results, we believe that it is important to point out several caveats. First, Radin and colleagues have highlighted that only certain subjects seem to impact the interference pattern. E.g. in their experiments only experienced meditators seemed to affect the interference pattern. We found something similar here. In Experiment 1 we succeeded in recruiting experienced meditators. However, we failed to do so in Experiment 3. The results in Experiment 1 indeed seemed much more promising than the results of Experiment 3.

Second, despite our best efforts, we did not succeed in recruiting a large number of experienced meditators. Given the supposed impact of the subject on the success of the task, this severely hampers any conclusions that can be drawn from our findings.

Finally, in retrospect we believe that our experiments can be improved in several ways. E.g. we should probably provide feedback on the mean of the interference pattern and then test whether the variance is changed, rather than providing direct feedback on the variance. Moreover, perhaps subjects can introspectively detect whether they can affect the interference pattern. However, to test this we should ask subjects what they think about this after the first few blocks and then apply our analyses only to the latter blocks, to avoid double dipping.

In conclusion, we believe that the current findings provide enough reason to continue replication attempts of Radin et al.'s findings. It is unfortunate that the logistical challenges are quite prominent. For instance, building the set-up for measuring interference patterns in a stable manner is not trivial. Moreover, recruitment of appropriate subjects can be a major hurdle as well. We have already built the set-up, so this will not pose a challenge in the future. To deal with recruitment challenges, we aim to extend collaborations with meditation researchers.

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Final report

Table highlighting the differences between expected and achieved output indicators

Expected and achieved output indicators (number of actions)

Output indicators	Expected (according to application)	Achieved
Advanced training: PhD theses	none	none
Advanced training: Master theses	none	none
Advanced training: Other	none	Two post-docs worked intensively on this project
Organization of seminars and conferences	none	none
Book	none	none
Book chapter	none	none
Conference presentation	none	none
Conference paper	none	none
Journal article	Several journal articles	We aimed for several articles, but our findings are not currently suited for publication. We believe that our failure to replicate can be due to several factors. Therefore we will continue to improve our studies and aim for more replications, rather than publish flawed data.
Other (specify)		

Notes:

List of publications