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Does Consciousness Collapse the Wave-Packet?

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Abstract

The "subjective reduction" interpretation of measurement in quantum physics proposes that the collapse of the wave-packet, associated with measurement, is due to the consciousness of human observers. A refined conceptual replication of an earlier experiment, designed and carried out to test this interpretation in the 1970s, is reported. Two improvements are introduced. First, the delay between pre-observation and final observation of the same quantum event is increased from a few microseconds in the original experiment to one second in this replication. Second, rather than using the final observers' verbal response as the dependent variable, his early brain responses as measured by EEG are used. These early responses cover a period during which an observer is not yet conscious of an observed event. Our results support the "subjective reduction" hypothesis insofar as significant differences in the brain responses of the final observer are found, depending on whether or not the pre-observer has been looking at the quantum event (exact binomial $p < 0.02$). Alternative "normal" explanations are discussed and rejected. It is concluded that the present results do justify further research along these lines.

1. Introduction

1.1 The Problem

Twenty-five years ago, Hall et al. (1977) reported an experiment that, according to their description, tested the most radical solution to the measurement problem in quantum physics, namely the proposition that *"... the reduction of the wave packet is a physical event which occurs only when there is an interaction between the physical measuring apparatus and the psyche of some observer"*. They commented their experiment writing *"... although we concur that there is a genuine problem of the reduction of the wave-packet, we do not intend in our paper to defend this opinion against those who maintain that it is a pseudo problem"* (Hall et al. 1977, p. 760).

In spite of many attempts, like the relative state approach (Everett 1957) and the introduction of non-linear terms in the Schrödinger equation

(Ghirardi et al. 1986), the measurement problem is still unsolved. This failure has left the physics community polarized with some contending the problem remains a fundamental shortcoming in the quantum formalism and others holding that there is no reduction of the wave-packet at all (Bohm and Hiley 1993, Griffith 2002, Dieks and Vermaas 1998). Costa de Beauregard (1976), Walker (1971, 1988, 2000) and Stapp (1993) have claimed, using arguments by von Neumann (1955) and Wigner (1964), that none of the proposed solutions are acceptable and that subjective reduction is still a possible and even preferred alternative.

As Hall et al., we do not wish to attack or defend this or any other position with regard to the proper interpretation of the quantum formalism and the role of measurement therein. As Hall and his collaborators, we would like to investigate this problem experimentally.

1.2 Hall's Experiment

The Hall experiment is conceptually easy to understand. A quantum event, in this case a radioactive decay event, is measured in a counter and the signal is displayed on a scaler. A "pre"-observer 1 observes the scaler. The scaler signal is transmitted through a delay unit and displayed again on a second scaler, which is observed by the "final" observer 2.

Observer 1 will sometimes observe, but sometimes not observe his scaler. Observer 2 has to "guess" if a quantum event observed by him has already been observed by observer 1 (see Fig. 1, from Hall et al. 1977).

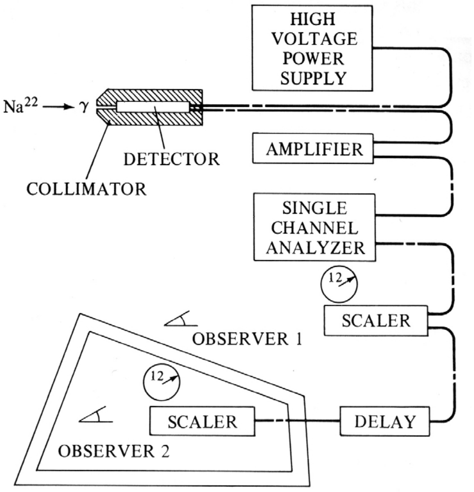

Figure 1: Experimental arrangement of Hall et al. (1977).

The results of this experiment were precisely at chance, i.e. the second observer guessed 50% correctly. Hence, it was obvious that this observer was unable to detect if the observed signal had already been observed earlier. It was concluded that the experiment does not provide support for the hypothesis that it is the interaction with consciousness that causes the wave-packet to collapse.

1.3 The Present Conceptual Replication

It is an implicit assumption of Hall et al. that our brains in some way are able to detect the difference between a superposition state and a reduced state. It is furthermore assumed that this difference can be communicated consciously.

In a comment later added to the article the authors noted that the used delay was extremely short and that *"... the delay time should be in the order of psychologically discriminable intervals ..."* (Hall et al. 1993, p. 331). Since their original paper has been widely acknowledged as evidence against the hypothesis that it is the interaction with consciousness that causes the wave-packet to collapse, it is essential that this serious error in the Hall experiment be corrected by means of further testing. It is important that both the time delay be of physiologically significant duration and that the determination as to whether the observers have been affected differently by the two conditions be placed on a more objective foundation than the verbal report used by Hall et al.

In the present conceptual replication the time between the first observation and the second one was set to 1000 msecs. Indeed Libet's seminal work on the processing time needed for conscious experience (Libet et al. 1979) sets a lower bound of about 300–500 msecs, because one should require the first observation to be conscious.

However, the difference between our replication and the original experiment goes a bit further than merely adjusting this time interval. Rather than asking the second observer for a conscious guess, we measure the brain response to the stimulus related to perceiving the quantum event. This is done for the following deficiency of the original experiment: If consciousness is the crucial element for wave-packet reduction, the conscious decision of the pre-observer, used as the dependent variable, will be based on the physical state of the wave-packet *after* the second observer has become conscious of the quantum event. At that time, the wave-packet according to the hypothesis under investigation has collapsed even if no pre-observation has taken place. Thus, the manipulation of the pre-observer will not induce any difference with regard to the consciousness of the final observer.

By measuring brain potentials of the second observer one can, however, also tap into the early (i.e. earlier than 300 msec) non-conscious processing of the brain. At that time the wave-packet is supposedly still in superposition, if no pre-observation has taken place.

2. Design of the Experiment

Quantum events were generated by an alpha particle source (as used in smoke detectors; 2P40-76-18) that was mounted on a slider allowing the source to be moved with respect to a lead-shielded Geiger–Müller counter (Automess 6150-100). The distance was set so that, on average, one particle was detected in about every second. The counter pulse was amplified and fed to the trigger channel of an EEG data-acquisition system.[1] We used *National Instruments LabView* software[2] to detect this trigger and transform it into a delayed audio-beep of 1500 Hz and 50 msec duration. The audio-delay was one second.

The software would randomly generate a visual stimulus of ≈ 65 msec duration directly upon the trigger. The visual stimulus, therefore, precedes the audio-beep by a time sufficient for the first observer to have conscious experience of the quantum event *before* the second observer (see Fig. 2). The random decision to show this visual stimulus to the first observer before submitting the beep to the second observer or not was pseudo-random with a seed determined by the computer clock. After each quantum event thus measured, there was a dead time of two seconds during which the input of the Geiger–Müller counter was discarded. The subjects were asked to count the number of observed quantum events.

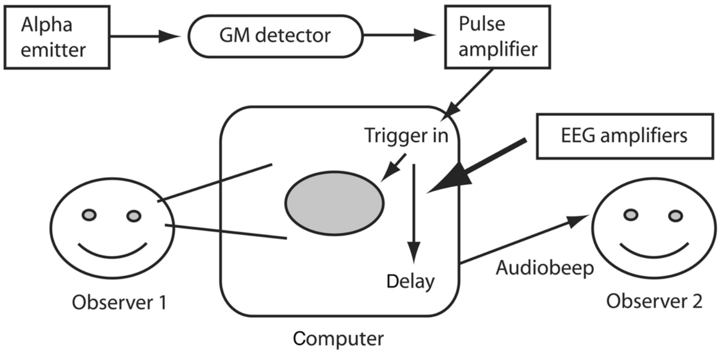

Figure 2: The experimental set-up of the present replication experiment.

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[1] The system is called *Biosemi Active-1*, see `http://www.biosemi.com`.

[2] See `http://www.ni.com`.

The quantum mechanical theory of radioactive decay describes the emitting particle as a superposition of two states, the decayed and the non-decayed state. Although our measurement system is a composite many particle system, it can be regarded as being in a superposition of a decayed and a non-decayed state as well. According to the radical proposition under consideration, this superposition is reduced, or collapses, if a conscious observation of either the visual or the audio representation takes place.

3. Experimental Procedure

3.1 Subjects

Volunteer subjects were invited in pairs. They were generally freshman psychology students who participated for course credit. In total, 9 males and 21 females participated in the experiment providing useful data (mean age 21.4, standard deviation 4.7). Two subjects were removed from the analysis because their brain signals were noisy due to a loose electrode.

Upon arrival, the subjects were fully informed about the purpose and potential implication of the experiment. First, they participated in a so-called odd-ball task used to test the equipment. Then the crucial task, called the “Schrödinger-task” for obvious reasons, was presented. The role of observers 1 and 2 were played by both subjects in two separate runs.

3.2 Physiological Measurement

Sintered AgCl EEG electrodes with active preamplifiers (*Biosemi Active 1*) were connected to the head of observer 2 using the standardized 10/20 system shown in Fig. 3. No temporal electrodes were used. Then observer 2 went to a neighboring room and was seated in a relaxing chair while observer 1 stayed at the computer screen with the experimenter. A short “calibration” experiment was run consisting of the above mentioned odd-ball task in which observer 2 was presented audio-beeps of 30 msec duration each 3 seconds (with one second random jitter). A hundred beeps with either a frequency of 1200 Hz or a frequency of 2000 Hz were presented. The frequency was randomly determined with the probability for the higher frequency four times as low as for the lower frequency. The subject was asked to count the higher frequency beeps. Their brain signals were sampled with a frequency of 2400 samples per second.[3]

If the resulting average evoked brain potentials conformed to the well-known average auditory odd-ball brain potential (Picton et al. 1974), the actual “Schrödinger” run was started with observer 1 sitting in front of

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[3] Raw Data are available at `http://a1162.fmg.uva.nl/~djb/research/eeg-data`.

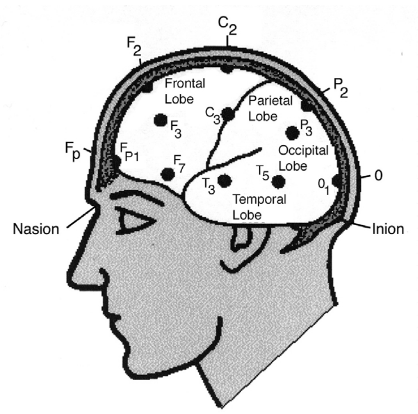

Figure 3: The 10/20 electrode placement system used in the experiment. See `http://faculty-washington.edu/chudler/1020.html`.

the computer screen and observing the visual stimulus that appeared in about 50% of the cases directly upon a radioactive decay event. The experimenter refrained from looking at this screen. The total run consisted of 120 radioactive decay events. This took about 8 minutes. After a short break roles were switched and the procedure was repeated. The total experiment took less than one hour per subject pair.

3.3 Further Procedure

To prevent ourselves from data snooping and data selection with the goal to "find what we were searching for", we first analyzed the results of the standard, and completely unrelated, odd-ball task. Once we had fixed the complete procedure on the basis of exploring the odd-ball task data we would allow ourselves to analyze the actual data.

The evaluation of the odd-ball data showed that two of the 32 subjects were not providing valid EEG data. Furthermore the odd-ball data were used to establish an optimal preprocessing procedure. This procedure consisted of four steps. All signals were re-referenced to (compared to) the signal at the Pz electrode. First, a 50 Hz notch filter was applied, then the data were filtered through a band pass filter between 1 and 30 Hz (slopes 24 db/oct). Then, (eye) movement artifacts were removed from the data according to their "absolute value" and "derivative". On average, this algorithm removed about 5–10% of the available segments.

Because there is a high correlation between the results obtained from different leads (electrodes) we did a factor analysis to see how we could combine the signals from different leads into a compound signal. This analysis yielded two clearly distinct factors, one consisting of the central and frontal leads with a mean factor load of 0.87 and one for the parietal electrodes with a mean factor load of 0.93. We called the two combined signals "FC" (which is the average of the 11 leads Fpz, Fp1, Fp2, Fz, F7, F3, F8, F4, Cz, C3, C4) and "P" (which is the average of the two leads P3 and P4).

4. Results

4.1 Evoked Potentials

After having thus established the data to be analyzed and a well specified preprocessing procedure, we applied this without further adaptation to the EEG data obtained in the "Schrödinger" part of the experiment. First we averaged all data pooled over subjects and pre-observer condition per sample for the FC- and P-signal separately.

Then, the obtained evoked potentials of the final observer were submitted to the automatic peak detection procedure of the standard BrainVision analyzer software. Results are shown in Fig. 4. For the combined frontal and central leads the peaks are denoted N20, P40, N100, P200, N300, P350, and N400 at exactly 17, 41, 95, 178, 292, 357, and 411 msec after stimulus onset.[4] For the two combined parietal leads, the peaks are denoted P100, N160, and N200 at exactly 99, 160, and 212 msecs after stimulus onset.

Note that in Fig. 4 the evoked potentials are still pooled over pre-observer conditions. In order to check if the pre-observation by a first observer makes a difference for the brain signals of the final observer, we have to split the data for the two pre-observer conditions. This is done in Fig. 5. Under the null-hypothesis (that pre-observation does not matter) there should be no difference.

4.2 Statistical Analysis of Peak Amplitudes

As usual in EEG data, the two traces for the two conditions do not completely coincide. In order to assess if the observed differences are statistically significant we did a simple comparison between the signal value at peak position for the pre-observed and the non pre-observed trials.

All peaks obtained by the automatic peak detection procedure were analyzed. In Tab. I, column 3, we list the differences for the peak amplitudes between the two pre-observer conditions. As mentioned above, these differences should be negligible if the fact that someone has observed the

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[4] The general convention in EEG plots is that positive (negative) voltage is plotted "downward" ("upward") and is referred to as P (N) plus the latency time with respect to stimulus onset.

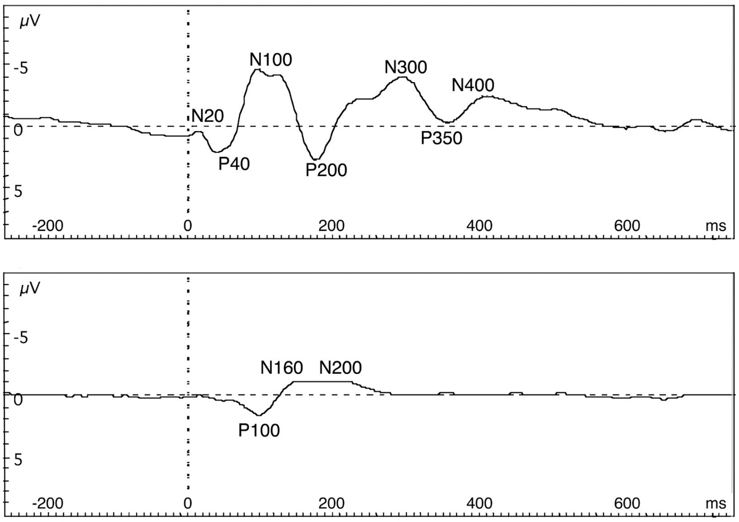

Figure 4: The mean evoked response for all subjects. Upper trace: all frontal and central leads (FC); lower trace: two parietal leads (P).

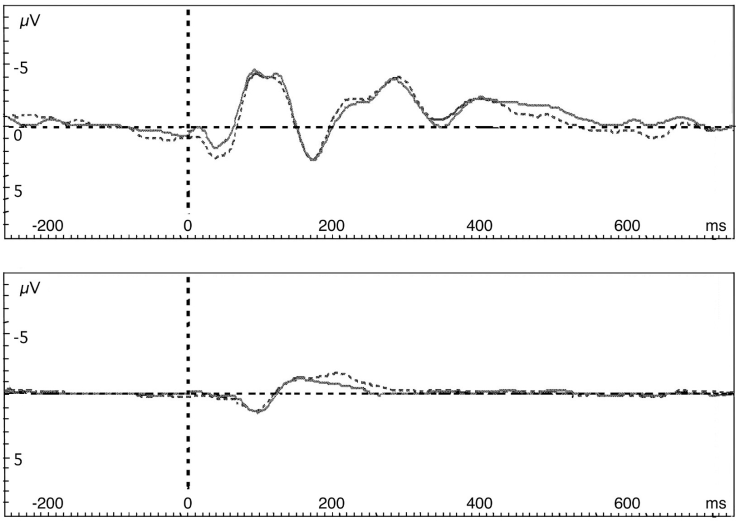

Figure 5: The mean evoked responses split for the two different conditions with respect to pre-observation. The solid line represents the pre-observation condition, the dashed line represents the condition without pre-observation. Upper trace: all FC leads; lower trace: two P leads.

same quantum event earlier does not matter. A standard t-test (column 4) was run to find the probabilities that the observed differences are due to chance (column 5). In order to assess the overall probability of these differences between the peaks we calculated the exact binomial probability of finding three significant differences (printed italic in column 5) in a total of 10 analyses. This overall probability turned out to be $p = 0.0115$.

Besides the results of the parametric t-test we also calculated the results of non-parametric binomial tests. In these latter tests the magnitude of the difference is irrelevant, only the direction for each subject counts. The nimber of subjects showing a peak value with a larger amplitude in the pre-observer than in the observer condition is given in column 6 of Tab. I. This is followed by the number of subjects with the reversed pattern and the associated binomial probability. It can be argued that the non-parametric test is more suitable since the differences between two evoked potentials are not necessarily normally distributed. An overall assessment of the non-parametric tests using the same binomial approach as above gives a total probability of $p = 0.0106$.

			df = 29		
	Peak	Difference (μV)	t	p	Non-param. p $N = 30$
FC-leads	N20	1.002	2.12	*0.043*	19-11 : 0.20
	P40	0.903	2.64	*0.013*	22-8 : 0.016
	N100	0.350	0.66	0.52	15-15 : 1.0
	P200	-0.09	-0.18	0.86	15-15 : 1.0
	N300	-0.04	-0.08	0.93	15-15 : 1.0
	P350	-0.54	-1.17	0.25	12-18 : 0.36
	N400	0.098	0.25	0.80	16-14 : 0.86
P-leads	P100	-0.16	-0.67	0.50	12-18 : 0.36
	N160	-0.152	-0.84	0.41	13-17 : 0.58
	N200	-0.956	-3.93	*0.0005*	7-23 : 0.005

Table I: Results of the differential analysis of the peak amplitudes.

From the results shown in Fig. 5 and evaluated in Tab. I, the following conclusions may be drawn:

1. With regard to the EEG-signal from frontal and central leads, there is a significant difference between the two pre-observer conditions in the very early peaks. This difference disappears after about 100 milliseconds.

2. On the parietal leads the difference is significant in the opposite direction and arises later with a clear maximum at 200 milliseconds.

5. Discussion

The results of these experiments support a solution of the measurement problem that assigns a special status for conscious observation in the measurement process. The absence of significant differences in the late evoked potential (latencies of 300 msec and more) appears to be consistent with the fact that in the original Hall experiment no differences were found when one asked the second observer to *consciously* express his feeling as to whether the observed quantum event had already been observed. Nevertheless, this result should be treated cautiously because of the lack of statistical power in the later phases of the response. This lack of power is caused by an increased variance with increasing latency times.

However, more mundane alternative explanations for the current findings are possible. They need to be carefully checked before far-reaching conclusions are drawn from our experiment.

5.1 Alternative Explanations

First, spurious sensory cueing of the second observer has to be considered. Both observers were in adjacent rooms which were not auditorily or electromagnetically shielded. The reason for having the first observer observe a *visual* representation of the quantum event rather than an audio-beep was indeed to prevent any audio leakage to the second observer. Nevertheless, ultrasonic or electromagnetic signatures from the monitor displaying the signal for the first observer might still have presented sensory cues. Thus, the second observer might have produced a slightly different auditory evoked potential due to ultra-sound related to this earlier pre-observation. This scenario, however, is not very plausible in that it would result in affecting the peaks in the evoked potential in a systematic way. The timing of the visual stimulus to the first observer and the delayed audio-beep to the second is not precise and therefore one can hardly expect a well-defined effect in time.

A second explanation might be due to an improper randomization of the pre-observer condition. It is well known that evoked potentials on simple stimuli like beeps tend to habituate (decline). Thus, the amplitude of the signal becomes smaller in the course of the experiment. If, for some reason, the randomization did result in a non-balanced distribution of conditions in time, this could artificially induce a differential effect due to habituation. We tested this possibility using the actual sequence of stimulus conditions as they occurred in the experiment with several habituation models. None of these models provided any effect (p-values around 0.77). As a further test of the validity of the peak differences found between the two pre-observer conditions, we "randomly" relabeled the markers, thus creating two pseudo-conditions for which we did exactly the same peak difference analysis. The result of this analysis was at chance level: the mean difference found was 0.16 microvolts at P40, which is six times smaller than the actually observed effect.

The current results look pretty robust, but they are not extremely improbable in terms of statistics. Although the applied overall assessment is a bit conservative since it treats the more significant peaks as being of the same significance as the less significant peaks, one could argue that the current findings might be attributed to chance with a probability of 1 in 50. Although this figure satisfies the criterion of 5%, the generally accepted significance level, it is not enough to unequivocally accept the hypothesis that consciousness collapses the state vector. Strong claims need strong evidence.

5.2 Future Work

A further crucial variant of the reported experiment, in which the radioactive source is at all times replaced by a classical source of events, is presently underway. For classical events, the differential pre-observer effect should disappear as the quantum character of the observed events is crucial. This work will be reported subsequently.

In addition, such replication studies enable us to predict more precisely where and when to look for differences in the brain signals. Another factor that can be explored is the role of a video camera, ensuring that an interaction of "states" of both observers enters the state description of the experiment. If such a camera is necessary for significant differences, it would follow that the current set-up does not refer to "signals" outside of the light cone and, hence, does not violate special relativity.

The concept of a conscious observation has not been worked out in detail so far. In Libet's work, which we used to estimate the delay between perceptual input and the conscious experience thereof, a conscious observation is by definition an observation which is stored in memory. However, there is suggestive evidence, for instance from "change blindness" experiments, that there is another form of "faster" conscious experience directly related to perceptual input (Landman et al. 2003). This experience is not stored in memory. In further work it might be necessary to discriminate between these and other possible forms of conscious experience.

In areas dealing with "artificial intelligence", such as cognitive sciences and the philosophy of mind, the question has arisen if computers can be "conscious" (with respect to a proper definition of this term). The reported work suggests that such a question might become empirically testable.

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