Probing Quantum Memory Effects in the Single Photon Regime

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In this paper we study correlations present in experimental random series extracted from a Quantum Optical Random Number generator conceived and implemented in our lab. In particular we study the manifestations of inertia/memory effects. This study is realized in the single photon regime.

1 Introduction

We learn from classical and quantum physics that the future properties of a physical system are determined by its instantaneous, present state. This is reminiscent of the so-called Markov property in statistics, according to which “...the conditional probability distribution of future states of the process, given the present state and all past states, depends only upon the present state and not on any past states...”

In previous papers (see [5] for a survey), one of us (T. D.) studied the possibility that quantum correlations exhibit non-Markovian features [4], in other words that quantum correlations would be endowed with an intrinsic, non-standard memory effect. Actually, several experiments were realized in the past, in different contexts, in order to test the possibility of such memory effects [2–4, 7]. These experiments aimed at testing hidden variable models (both local and non-local models [5]) which predicted the appearance of non-standard correlations between measurement outcomes collected at different times (different places in the case of non-local models [2]). We shall not enter in the detail of these experiments and models here, but instead we shall focus on the results of a statistical test that we developed in the past in order to characterize quantum random number generators that were developed at the Université Libre de Bruxelles (U.L.B.) and Vrije Universiteit Brussel (V.U.B.). We developed this test, from now on denoted the Histogram Inertia Indicator (H.I.I.) test in order to reveal whether histograms constituted from data measured at different times were correlated to each other.

Besides the aforementioned hidden variable models, we found inspiration in the idea of morphic resonance expressed and developed by Rupert Sheldrake [17] according to which the evolution of species and development of life in general are characterized by memory effects having as a consequence that new shapes/patterns tend to behave as attractors for other shapes/patterns. In a previous paper we showed that mixing Sheldrake’s ideas and hidden variable models led to the prediction of observable non-standard memory effects (see [4] section 3: Sheldrake and Smolin’s Models, and a Related Experimental Proposal).

Fig. 1: SeQuR QRNG - Raw Data: A “near zone” effect is clearly present in the SeQuR data (blue graph). Successive histograms, each drawn from 1000 sequential random values, exhibit a manifest tendency to resemble each other. The green graph represents the same test on a Matlab pseudo-random series. The red lines represent the boundaries that are assigned to “perfect” random series. The plotted p-values confirm the results in graphical form. (quoted from [19])

Our main goal, when we developed the H.I.I. was to try and reveal whether quantum histograms would exhibit memory effects. It can be seen as an attempt to extrapolate the extent of validity of Sheldrake’s ideas to the quantum realm.

A last source of inspiration was provided by the evidence for annual periodicity in decay data [9, 10] that has been revealed a few years ago. It has been suspected that this periodicity cannot be explained by environmental effects such as temperature, humidity, pressure, etc [11], nor is there a correlation with the Sun-Earth distance after re-analysis of the data [13].

All these observations suggest that there could exist some “regularity in randomness”, some “hidden” pattern, a non-standard memory effect characterized by correlations between data collected at different times. This is a very upsetting and at the same time challenging idea which deserves to be considered seriously, from a foundational perspective [2–5, 7].

In particular we noticed the presence of an intriguing memory effect already some years ago [19], at the level of a random optical signal measured in the continuous counting

†Quoted from Wiktionary.
regime (see section 2.3). The data were delivered to us by colleagues from the U.L.B. developing a prototype of ultra-fast quantum optical random number generator [6]. Essentially, this device amplified fluctuations of the intensity delivered by a laser source. The results plotted at the level of Fig. 1 reveal for instance a clear deviation from the theoretical boundaries (in red) associated to a fully random process (without memory effect). We also checked in the same work [19] that Fourier filtering and/or Faraday filtering diminishes the effect, but does not suppress it totally. Our interpretation of these observations is that these correlations could be partially due to an external mechanism, and partially due to the internal memory of the device (here the light detector which is acting in the continuous (many photons) regime).

It was not clear however, uniquely on the basis of the observations, to decide whether the external source of the correlations had to be attributed solely to electromagnetic pollution (GSM devices, FM radio channels and so on) or whether it was necessary to resort to a universal memory effect in order to explain our observations.

Therefore we decided to test experimentally similar memory effects in the low intensity (single photon) regime, which was made possible by the development of quantum random number generators (QRNG) active in the low intensity (discrete counting) regime in situ in our labs and based on the random character of time delays between clicks collected with a single photon avalanche detector at the output of an attenuated laser source. The corresponding generator, the so-called Parity Quantum Optical Random Number (PQORN) generator has been described in a separate publication [6] and is briefly described in section 3.1 (see also Fig. 2).

As we shall describe in the present paper, we applied the H.I.I. test to the raw data generated with our PQORN generator. This program is triply challenging in our eyes because, as far as we know, nobody tested in the past the existence of memory effects by the same method, and a fortiort no such test has been achieved so far in the low intensity regime. Last but not least, if the memory effect revealed by the H.I.I. indicator is universal, its detection provides a criterion for discriminating physical randomness from pseudorandomness which is a very challenging idea.

The paper is structured as follows. We describe in section 2 a new statistical test, the H.I.I. test, introduced in [19] aimed at measuring and/or revealing memory effects (section 2.1), as well as the corresponding p-value (section 2.2). Our methods are also relevant in the framework of random number generation because the H.I.I. test and the associated p-value are thus useful tools in order to characterize randomness.

Before scrutinizing (making use of the tests described in section 2) the existence of memory effects at the level of the PQORN generator (section 4), we investigated more in depth the correlations which appear in the high intensity regime at the level of our single photon detectors (section 3.2). These correlations are a priori not of quantum nature but they are induced by the dead time of the detector. As we show in section 4, in the high intensity regime, and only in this regime, the H.I.I. memory effect is present.

We also studied whether similar memory effects still exist beyond the near zone regime studied in section 4.1, and in particular whether non-local in space (section 4.2) and time (section 4.3) memory effects (previously denoted Spatial and Temporal Long Range Memory effects) can be measured at the level of our device. The last section is devoted to the conclusions and to the interpretation of the collected results.

2 The near-zone H.I.I. test

2.1 Qualitative test

In order to derive a statistical test aimed at revealing memory effects, we approached the problem as follows [19]: Each histogram of a given data sample – given it is not too large

Fig. 2: Detailed setup for the near-zone experiment. It is composed of a laser source, two neutral density filters and a single photon detector. The same setup, supplemented with a nanosecond resolution clock constitutes the Parity QORNG.

Fig. 3: Fluctuations of a sample histogram - constructed from 1000 gaussian distributed random data values - around the line of the average histogram computed from a data sample of 10 000 000 gaussian distributed random values.
Considering that the random sequence of length $n$ in $M$ two neighboring histograms, $\lfloor N \rfloor - 1$ values of $r$ for each of the $M$ samples, since we choose each histogram to be created from 1000 random values. Fig. 5 depicts graphical results after calculating all $r$-values.

This is only the first part of the investigation since, as one can deduce from Fig. 5, often, not much can visually be said about a possible “near-zone” effect. Therefore, it is appropriate to perform a statistical treatment of the data.

Fig. 4: The difference $\bar{H}$ of a sample histogram $H$ with the average histogram.

– fluctuates around the average histogram, which is obtained from a very large data sample, cfr. Fig. 3. For each histogram $H$ we compute its difference with the mean histogram. This leaves us with a new normalized histogram $\bar{H}$ in which each value can either have a positive of a negative value, depending whether that value is observed more or less often than in average, as shown in Fig. 4. Thereafter, we introduce a quantitative “resemblance” value $r$ as follows. Consider $\bar{H}_i$ and $\bar{H}_j$ two neighboring histograms.

$$r_i = \sum_a \bar{H}_i a \bar{H}_j a, \quad (with \ j = i + 1)$$

(1)

with $a$ the corresponding value of the histogram at this entry. Remark that we are working with histograms where values can be both positive and negative. Consequently, the inproduct $r$ can be either positive or negative. The following interpretation can now be given to $r$:

- $r$ is large and negative: Both histograms seem to be inverse of each other for most of the entries. The histograms have no near zone effect. Instead this suggests an anti- or complementary- “near-zone” effect.

- $r$ is close to zero: Both histograms have approximately as much resemblance as difference. Again no “near zone” effect is observed.

- $r$ is large and positive: Both histograms have the same shape for most of their entries. A “near zone” effect is then observed.

Considering that the random sequence of length $n$ is divided in $M$ data samples of length $N$, this analysis leaves us with $\lfloor N \rfloor - 1$ values of $r$ for each of the $M$ samples, since we choose each histogram to be created from 1000 random values. Fig. 5 depicts graphical results after calculating all $r$-values.

Let us start by taking the average of all $r$ inproducts:

$$\bar{r} = \frac{\sum_{i=1}^{M-1} r_i}{M - 1}$$

(2)

Since the analysis is performed on $M$ data samples of length $N$, each of the $M$ samples now leaves us with one value of $\bar{r}$. These $M$ average values $\bar{r}$ provide us with a qualitative indication of a “near zone” effect that we choose to express through the ratio of positive averages of $\bar{r}$, i.e.

$$\frac{\#\bar{r}}{M}$$

(3)

with $\#\bar{r}$, the amount of $\bar{r} \geq 0$. Note that the sign of $\bar{r}$ can be regarded as a Bernoulli process, or as a bit sequence with for example a bit value of 1 corresponding to a positive value and a bit value of 0 to a negative one. In a perfectly random process the ratio between them should be close to 1/2 with a deviation depending on $M$, the amount of data samples. In order to determine the magnitude of this deviation we consider the law of large numbers to derive the boundaries:

$$\frac{\#\bar{r}_{pos}}{M} \sim \frac{1}{2} \pm \frac{\sigma_{\bar{r}_{pos}}}{\sqrt{M}} = \frac{1}{2} \left(1 \pm \frac{1}{\sqrt{M}}\right)$$

(4)

with $M$ the amount of data samples or the amount of values $\bar{r}$. For a data set of length $n$, $M = \lfloor \frac{n}{N} \rfloor$ so that the boundaries also depend on $N$.

It is expected for perfect random processes that the magnitude of the ratio of positive averages $\bar{r}$ will remain confined within the boundaries plotted in Fig. 6. One expects that sporadically $\bar{r}$ will be found outside the boundaries but in the case that it will remain persistently outside the boundaries we must suspect that the random sequence is biased. Considered so, we now have at our disposal a qualitative test aimed at testing the presence of the near zone effect. In the next section, we shall also derive a quantitative criterion, in the form of a $p$-value.
Making use of the law of large numbers, the $p$-value can be shown [19] to be equal to

$$p\text{-value} = \text{erfc} \left( \frac{Z}{\sqrt{2}} \right).$$

### 2.3 Near zone memory effect in the continuous counting regime

Some years ago [19], we investigated the existence of a memory effect at the level of an optical random number generator the SeQuR QRNG, acting in the continuous regime. Essentially, the device amplifies the fluctuations of the intensity delivered by a laser source [6]. We considered the decimal random data delivered by the detector. The tested results show clear similarities in the successive histograms from the data samples. This can be observed in Fig. 1, quoted from [19]. This analysis clearly indicates the presence of an inertia or memory effect in the signal. Let us now consider discrete data collected with single photon detectors.

### 3 Randomness in the low photon number regime

#### 3.1 Parity QORNG

The Parity QORNG exploits the random nature of the distribution of clicks in a single photon detector. It is based on the parity of the time (in nanoseconds) for which the events (clicks) occur. If this time is even, the bit will be zero; if this time is odd, the bit will be one. The set-up to carry out this method consists of an attenuated laser source coupled to a single-photon detector (Fig. 2). The detector is coupled to a buffer via an acquisition card synchronized with a clock of high resolution (1 nanosecond).

As has been shown in [6], the principal advantages with this method are 1) that it requires to use only one photon-detector to generate a random number and 2) that even in the high intensity regime it delivers random series of very high quality.

Before we characterize the H.I. effect, let us study the physical correlations exhibited by the single photon detectors of the parity QORNG.

#### 3.2 Study of correlations due to dead-time of detectors

##### 3.2.1 Successive clicks in one single-photon detector

In this section we will check the statistical properties of the data acquired in single-photon detectors in various regimes. These regimes are reached by modifying the attenuation of our two tunable attenuators (Fig. 2), from almost no attenuation at all to a high attenuation.

Before going further it is worth recalling that the single-photon detector is characterized by a dead time (that is to say the lapse of time during which the photon-detector will be off after detecting a photon) in the range of 45 to 50 ns. The resolution time of the acquisition card is 1 ns, therefore every 1 ns a datum will be acquired, while the maximum data that the acquisition card can memorize is 750 000 ns, after which the memory of the acquisition card is full.

For instance bit series obtained from the PQORNG successfully pass [6] the NIST battery of standard randomness tests (frequency test, parity test, spectral test, entropy test and so on).
Fig. 7: Statistics of time arrival between photons in the high intensity regime. Average time between photons estimated to be more or less 36 ns.

Taking into account the specifications above, we performed a study of the time arrival between two photons in different regimes changing the attenuation. For instance, in the high intensity regime (low attenuation regime) we observe a distribution of delay times between clicks plotted in Fig. 7 which is contaminated by the correlations induced by the dead-time of the detector (as revealed by the presence of peaks separated by 45 ns). From the tail of the semi-logarithmic plot, we can infer the average time between two photons, which would be exactly the slope of the straight line if the distribution was Poissonian, which corresponds to a dead time equal to zero.

If in turn we work in a low intensity regime, for which the average time between two clicks is quite larger than the dead time of the detectors, we observe a nearly Poissonian distribution, as can be seen from Fig. 8. The single noticeable difference with a Poisson distribution is the null probability to measure successive clicks in a time smaller than the dead time (here 45 ns).

3.2.2 Simultaneous clicks in two single-photon detectors

In order to check the departure from the Poisson distribution, we estimated another parameter which is the number of simultaneous counts in two detectors placed at the output of a beamsplitter. When two photons arrive at the exact same time to the beamsplitter, there exist four possible scenarios (Fig. 9):

1. Both photons are detected by the photon-detector A.
2. Both photons are detected by the photon-detector B.
3. Photon A is detected by the photon-detector A and photon B is detected by the photon-detector B.
4. Photon A is detected by the photon-detector B and photon B is detected by the photon-detector A.

The probability of obtaining a single photon during a unit-period of time is (in case of a perfectly Poissonian distribu-

Fig. 7: Statistics of time arrival between photons in the high intensity regime. Average time between photons estimated to be more or less 36 ns.

Fig. 8: Statistics of time arrival between photons in the low intensity regime. Average time between photons estimated to be more or less 294 ns.

Fig. 9: Possibilities that two photons are detected by two photon-detectors.
The probability of obtaining two photons at the input of the beamsplitter is then:

\[ P(\text{pair}) = \left( \frac{1}{\text{average time between photons}} \right)^2 \frac{1}{2!} \]  \hspace{1cm} (9)

Henceforth, the probability that two photons arrive during a same temporal window unity in the two photon-detectors can be calculated theoretically:

\[ P(\text{double count}) = \left( \frac{1}{(\text{average time between photons})^2 \cdot 2!} \right) \frac{1}{2} \]  \hspace{1cm} (10)

The average number of double clicks obeys therefore

\[ N(\text{double counts}) = \left( \frac{\text{total number of photons}}{\text{average time between photons} \cdot 2!} \right) \frac{1}{2} \]  \hspace{1cm} (11)

In the high intensity regime we found a significant departure from the Poisson distribution:

- Total number of photons \( \approx 640000 \).
- Average time between photons \( \approx 21 \) ns.
- Simultaneous clicks in the 2 photon-detectors \( = 4999 \).

\[ \left( \frac{640000}{21 \cdot 2!} \right) \frac{1}{2} \approx 7619 \]  \hspace{1cm} (12)

In the low intensity regime we found a better agreement:

- Total number of photons \( \approx 184000 \).
- Average time between photons \( \approx 141 \) ns.
- Simultaneous clicks in the two photon-detectors \( = 272 \).

\[ \left( \frac{184000}{141 \cdot 2!} \right) \frac{1}{2} \approx 326 \]  \hspace{1cm} (13)

This confirms that when the dead time is small compared to the average time between two photons, the statistics of counts is Poissonian in good approximation, which fits with the standard quantum prediction for a coherently attenuated laser source. From this point of view, the limit of low intensities corresponds to the genuinely quantum regime, while in the high intensity regime (for which the dead time is comparable to the average time between two photons) quantumness is spoiled by correlations induced by the dead time mechanism of the detector.

Incidentally, our study also confirms that we nearly always operate in the single photon regime; the probability to have two photons or more in the same interval of acquisition (one nanosecond) being at most of the order of \( 10^{-2} \), even in the “high” intensity regime.

4 Characterization of the PQORN generator using the H.I.I. test

4.1 Near-zone temporal memory effect

The existence of a near-zone temporal memory effect would be revealed through the fact that similar histograms are significantly more probable to appear in the nearby (neighbouring) intervals of the time series of the results of measurements.

Using the setup in Fig. 2, we measured this effect in the two different regimes, the low intensity regime and the high intensity regime (they were defined in terms of the dead time at the end of the previous section).

To determine whether the effect is present, we make use of the H.I.I. test described in section 2, which delivers a \( p \)-value and a graph for a fast visual appreciation. We applied a level of significance of 0.01 for the \( p \)-value, hence if the \( p \)-value delivered is lower than the level of significance, we assumed that the presence of a significant memory effect gets confirmed by experimental data. Similarly, if the curve provided by the test remains outside the boundary curves, we assume that the existence of a memory effect is experimentally confirmed. We also used a standard auto-correlation test [6, 12, 16] to corroborate the results of the H.I.I. test.

4.1.1 Low intensity regime

We firstly measured the effect in the (highly attenuated) low intensity regime. We observed no correlation in this regime, as it is shown in Fig. 10. The H.I.I. test gives us the option to choose arbitrarily the sample length, which optimally ought to be of the order of the memory time of the H.I. effect. We selected four different sample lengths of 100, 300, 500 and 1000; and for each choice of a sample length, we tested the possible existence of a memory effect with the first, the second, the fifth and the tenth neighbour. For instance selecting 100 as a sample length, the reference sample runs from 1 to 100, the first neighbour sample from 101 to 200, the second neighbour one runs from 201 to 300, the fifth neighbour sam-
Fig. 11: Memory effect for the low attenuation regime with sample length of 100 for the first(a), the second (b), the fifth(c) and the tenth neighbour (d).

Fig. 12: Autocorrelation for the high intensity regime.

4.1.2 High intensity regime

We measured again the correlations in the high intensity (weakly attenuated) regime and Fig. 12 shows that in this regime a strong auto-correlation prevails until the bit 600 approximately. We also measured the memory effect in the same way as for the low intensity regime, i.e. for different sample lengths (100, 300, 500 and 1000) and different neighbours (1st, 2nd, 5th and 10th). From Figs. 13, 14, 15 and 16, it can be seen that for a sample length of 100, the H.I. effect is present. On the other hand, for a sample length of 1000, the experimental curve stays inside the red boundaries most of the time. Actually, when two samples separated by less than say 1000 bits are compared, the memory effect is present, otherwise there is no H.I. effect. These results are corroborated by the auto-correlation (Fig. 12) which is strong until the bit 600 approximately. They also fit with the average $p$-values shown in Tab. 6.

4.2 Long range spatial H.I.-like correlations

In a previous paper [4], one of us (T. D.) predicted that similar histograms are highly probable to appear at different geographical points at the same time on the basis of a genuine quantum hidden variable model incorporating the morphic resonance concept of Sheldrake [17]. We conceived a new experiment in order to study this prediction, based on the setup of Fig. 17, which is composed of two sub-setups (sub-setup A and sub-setup B). Each sub-setup consists of one source, one neutral density filter and one photodetector and is equivalent to the set-up described in the previous section that we used for testing the near-zone effect. The two sources are launched at the same time. In a first time we implemented the same H.I.I.
Fig. 13: Memory effect for the high intensity regime with sample length of 100 for the first (a), the second (b), the fifth (c) and the tenth neighbour (d).

Fig. 14: Memory effect for the high intensity regime with sample length of 300 for the first (a), the second (b), the fifth (c) and the tenth neighbour (d).

test as in section 4.1 separately for each detector in order to check that each individual subset-up exhibits the near-zone memory effect. This can be seen for instance at the level of Tab. 1. The period of the near-zone memory effect is of the order of 500 clicks, as is corroborated by the auto-correlation tests in Figs. 18a and 18b.

In a second time, we adapted the H.I.I. test in order to be able to detect H.I.-like correlations between the two subset-ups. We have thus to compare the random series of time delays obtained in one photodetector (series A) with the random series obtained in the other photodetector (series B). Comparing both of them will determine whether the histograms are
similar or not. In order to do so, a fixed sample length is selected (in our case, 100, 300, 500 and 1000) and we compare the histogram built from samples of this length extracted from series A with the corresponding histograms from series B, i.e. sample 1-100 of series A with the sample 1-100 of series B. We also compared neighbour histograms, like we did in section 4. This time we compare one histogram of series A with the neighbours of series B, i.e. for the first neighbour, sample 1-100 of series A with sample 101-200 of series B. We extended this procedure for the second, third, fifth, tenth and twentieth neighbour too. The results are encapsulated in Tab. 7. The average $p$-values are always quite larger than
0.01, for all the cases, which shows that no observable spatial H.I.-like effect is present at the level of our experimental setup, even in the high intensity regime where individual set-ups exhibit a near zone memory effect. We checked by similar methods that in the low intensity regime no spatial H.I.-like effect is present. In both regimes we also scrutinized the graphical presentations of the test results (that we do not reproduce here in order not to overload the presentation), which confirmed the conclusions already drawn from the estimate of the $p$-values.

4.3 Long range temporal memory effects

The aforementioned periodic modulation of radio-active emission with a period of about 365 days [9, 10], suggests that the phenomenon has a cosmophysical origin. We therefore investigated the possibility to generalize these observations in the case of a quantum signal. We focused on the 24-hour period experiment due to the large amount of time that we would have spent in tracking yearly memory effects. The 24-hour period would be an indication of the existence of an external agent that influences the object of study, most probably the rotation of the Earth. Our aim was to probe the existence of this effect at the level of the quantum signal obtained from our QRNG. For our experiment we used the same setup as in the near-zone experiment in section 4. It consists again of a laser source, a collimating lens, two neutral density filters and one avalanche photo-diode.

In February 2015, we realized a series of experiments, after having synchronized our computer clock with an atomic clock from the nist.gov website in such a way that all the measurements were automatized. Then, the runs were performed at exactly the same time every day for three consecutive days and we performed 20 different experimental runs with an interval of 20 seconds between each of them.

We estimated, based on the slope of the semi-logarithmic plot of the histogram of delay times, the average time delay and we found that the drift was small, with average times comprised in the interval 45-52 ns. Thereafter we estimated the individual H.I.I. $p$-values which measure the cross-correlations between the samples of days 1 and 2, of days 2 and 3, and of days 1 and 3. The results are encapsulated in Tab. 2.

<table>
<thead>
<tr>
<th>Sample Length: 100</th>
<th>A</th>
<th>B</th>
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<tbody>
<tr>
<td>1 neighbor</td>
<td>0.0036</td>
<td>0.0033</td>
</tr>
<tr>
<td>2 neighbor</td>
<td>0.0071</td>
<td>0.0036</td>
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<tr>
<td>3 neighbor</td>
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<td>10 neighbor</td>
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</tr>
<tr>
<td>20 neighbor</td>
<td>0.3191</td>
<td>0.3168</td>
</tr>
</tbody>
</table>

Tab. 1: $p$-values for the two sub-setups with a sample length of 100 bits for different neighbours (first, second, third, fifth, tenth and twentieth).

Carlos Belmonte et al. Probing quantum memory effects in the single photon regime
Our main goal was to study experimentally whether or not a memory effect of the H.I. type was present in the single photon regime. We developed a new, self-cooked algorithm, described in section 2 in order to realize this objective.

At first sight we ought to expect 0.1 instead of 0.15, but we must have in mind that the p-value derived by us corresponds to a situation where the effect of the H.I. type was present in the single photon regime effects in the single photon regime persisting after 24 hours. We consider therefore that our observations confirm the existence of long range temporal H.I.-like correlations of periodicity of the order of 24 hours, which appears, at least in our eyes, to be a very surprising result.

5 Conclusions and discussions

In this paper we studied the H.I. effect, which, roughly, would manifest itself through a tendency of random series to present analogous departures from their mean statistical behaviour. This tendency would possibly characterize data collected in the same temporal interval (what we denoted the near zone memory effect) but could present non-local features (non-local in time and/or space), what we denoted the long range temporal (resp. spatial) memory effect.

Our main goal was to study experimentally whether or not a memory effect of the H.I. type was present in the single photon regime. We developed a new, self-cooked algorithm, described in section 2 in order to realize this objective.

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Our conclusions are the following:

A) The near-zone H.I. memory effect is well present in the single photon regime, but only in the high intensity regime (for which the dead time is comparable to the average time between two photons). As we discussed in section 3.2, the limit of low intensities (when the dead time is quite larger than the average time between two photons) corresponds to the genuinely quantum regime, and in this regime no memory effect is present. This goes in the sense of the conclusion [19] drawn from the study of the SeQuR QORNG, for which the H.I. effect could be explained in terms of external electromagnetic pollution, combined with an internal memory time (inertia) of the photodetector. The persistence of H.I.-like correlations after 24 hours (that we address below) is however more difficult to explain. Anyhow, we can safely conclude from our experiments and our analysis that “pure” quantum random series, collected in the low intensity single photon regime do not exhibit any kind of observable H.I.-like correlation.

B) We were unable to observe manifestations of a long range spatial memory effect but detected a systematic tendency indicating the possible presence of the long range temporal memory effect, even after 24 hours. Our preliminary result ought to be of course confirmed by supplementary studies. The door remains thus open for what concerns the “daily” effect. It is worth noting that, even if this effect gets definitively confirmed, its interpretation is not straightforward. It is well-known for instance that some noises in nature (and in particular at the surface of our planet) exhibit a 24 hours period. It could be that the daily memory effect merely reveals this feature.

In any case, we hope that, beside contributing to a better understanding of fundamental aspects of quantum randomness*, our study also brings new tools aimed at characterizing randomness in general. We actually consider that the H.I.I. test provides a new statistical test, complementary to the standard NIST tests, and in particular to the auto-correlation test.

As we have shown (e.g. in section 4.1.2), at the level of physical random number generators, when auto-correlation is present, the H.I. effect is most often present too, which is already remarkable in itself and suggests the existence of a universal memory effect. Moreover, as shown in section 4.3, the long range temporal H.I. effect provide an example where the H.I.I. test reveals a systematic tendency, even in absence of auto-correlation (we checked for instance that the auto-correlation between data collected at different days (1,2,3) was uniformly flat).

We are still far away from one of our initial motivations, which was to be able to discriminate between physical randomness and pseudo-randomness thanks to the H.I.I. test1.

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Tab. 5: p-values extracted from the H.I. test for the low intensity regime for different sample lengths and different neighbours.

<table>
<thead>
<tr>
<th>Sample Length</th>
<th>1st Neighbor</th>
<th>2nd Neighbor</th>
<th>5th Neighbor</th>
<th>10th Neighbor</th>
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<td>0.4762</td>
<td>0.6031</td>
<td>0.6048</td>
<td>0.3997</td>
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<tr>
<td>300</td>
<td>0.4515</td>
<td>0.5647</td>
<td>0.4537</td>
<td>0.5269</td>
</tr>
<tr>
<td>500</td>
<td>0.5323</td>
<td>0.3049</td>
<td>0.4101</td>
<td>0.4614</td>
</tr>
<tr>
<td>1000</td>
<td>0.4105</td>
<td>0.4745</td>
<td>0.5121</td>
<td>0.2665</td>
</tr>
</tbody>
</table>

Tab. 6: Parity Method: Results of the file generated with the Split Method applying the NIST test battery.

<table>
<thead>
<tr>
<th>Sample Length</th>
<th>0th neighbour</th>
<th>1st neighbour</th>
<th>2nd neighbour</th>
<th>3rd neighbour</th>
<th>5th neighbour</th>
<th>10th neighbour</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.4330</td>
<td>0.5725</td>
<td>0.4067</td>
<td>0.4844</td>
<td>0.4530</td>
<td>0.5348</td>
</tr>
<tr>
<td>300</td>
<td>0.4608</td>
<td>0.5303</td>
<td>0.2870</td>
<td>0.2363</td>
<td>0.3765</td>
<td>0.3965</td>
</tr>
<tr>
<td>500</td>
<td>0.4508</td>
<td>0.4930</td>
<td>0.5378</td>
<td>0.4623</td>
<td>0.3572</td>
<td>0.0361</td>
</tr>
<tr>
<td>1000</td>
<td>0.5029</td>
<td>0.4965</td>
<td>0.4373</td>
<td>0.3953</td>
<td>0.2483</td>
<td>0.1399</td>
</tr>
</tbody>
</table>

Tab. 7: p-values when series A and B are compared for different sample length (100, 300, 500 and 1000 bits) for different neighbours (first, second, third, fifth, tenth and twentieth).

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and the low intensity case provides a counterexample to the mere possibility of doing so in general, but at least, our measurements confirmed that the H.I. effect is present in nature in various regimes. In particular it is weakened but still present after a delay of 24 hours, which is very amazing. Therefore we are intimately convinced that it is important to pursue these investigations. For instance it would be interesting in the future to compare results obtained with our algorithm and those obtained by Shnoll and coworkers, making use of a quite different algorithm [8,14,18], and applying it to noise [15], not to quantum signal as we did, which addressed relatively short series of data (of the order of 30 clicks only), contrary to ours, where we systematically made use of the law of large numbers in order to estimate \( p \)-values.

Last but not least, it would be interesting to study the appearance of the H.I.-effect at various temporal and spatial scales, the present work constituting only a first probe in this direction.

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References