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ORIGINAL PAPER

Quantum Theory Beyond the Physical: Information in Context

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Abstract Measures and theories of information abound, but there are few formalised methods for treating the contextuality that can manifest in different information systems. Quantum theory provides one possible formalism for treating information in context. This paper introduces a quantum inspired model of the human mental lexicon. This model is currently being experimentally investigated and we present a preliminary set of pilot data suggesting that concept combinations can indeed behave non-separably.

Keywords Information · Context · Concept combination · Non-separability · Separability tests · Generalised quantum model · human mental lexicon · Spreading activation · Spooky activation at a distance

1 Contextual Information

There are many varieties of information. Today, the Shannon measure [19] is almost synonymous with the term information, but this need not be the case. Shannon's measure computes the information attributable to an event as depending upon the probability (Pr) of an event e_k occurring from among a set of possibilities: $I(e_k) = -\log \Pr(e_k)$. This measure makes no reference to the content of the event;

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all events with the same probability of occurring will be attributed the same information content. While this at first seems rather implausible to the layman, Shannon style measures of information have proven remarkably successful within their domains of application [13]. However, humans are remarkably adept at extracting information within a specific context, a case which Shannon-style measures do not treat properly. Indeed, standard information theory remains silent on semantics: "the meaning of a natural language fragment, if 'meaning' has a real world correlate, is beyond the science of information", p. 157, [13], but this is clearly inadequate. In this paper we shall start to develop a more semantically motivated notion of *contextual information*.

We shall do this through the consideration of a set of models of the human processing of semantic information that were inspired by quantum theory. This approach allows us to incorporate contextual effects into the meaning that is attributed to a word by a human. While in their early days, the naturalness of these models is promising, and a recently performed experimental test seems to suggest that humans may indeed exhibit quantum-like effects when they attribute meaning to ambiguous words. Indeed, in Sect. 2.2 we shall make use of the expected value $E(e) = \sum_{k=1}^{n} e_k Pr(e_k)$ to examine the possibility that the meanings which humans attribute to ambiguous words cannot be considered separably. Upon comparison with the Shannon measure, we see that these two quantities are similar enough, both being based upon the probability of an event $P(e_k)$, to make us suspect the appropriateness of the Shannon measure when considering the information content of a word.

We shall begin with a very brief introduction to the modelling of word associations in the human mental lexicon.

1.1 The Human Mental Lexicon

How do humans understand language? Every day, we are confronted with novel words and combinations, often in completely new contexts, and yet we are usually able to extract sensible meanings from these. This complexity can be illustrated by considering one simple word, for example "bat". This word has at least two senses in its noun form; it might refer to a flying mammal that lives in caves, or alternatively it might refer to a sporting implement (and a variety of these are possible). Generally we can tell the sense that another speaker intends through a consideration of the context in which the word appears. Thus, if I were to claim that "the bat flew over the horizon" then it is unlikely that a listener would think I was talking about a sporting implement. They would be far more likely to decide that I was talking about an animal. The context in which the word appears is key to its interpretation.

These different *senses* of a word have been thoroughly explored over decades using a number of different psychological methods, and a wide range of data obtained.

One simple experiment involves cueing a subject with a word, and asking them to list a free associate. Much data of this form has been gathered over a span of decades. For example, the University of South Florida (USF) free association norms [16] give a set of free association probabilities for a set of 5,019 cue words.

According to this data, when used as a cue word, “bat” produces “ball” 25% of the time, ‘cave’ 13% of the time etc.

We can also find out which words are likely to produce the word “bat” (now called a target). One way of achieving this involves a process known as *extralist cuing*. Here, subjects typically study a list of to-be-recalled target words shown on a monitor for 3 s each (e.g. “bat”). The study instructions ask them to read each word aloud when shown and to remember as many as possible, but participants are not told how they will be tested until the last word is shown. The test instructions indicate that new words, the test cues, will be shown and that each test cue (e.g., “ball”) is related to one of the target words just studied. These cues are not present during study (hence, the name extralist cuing). As each cue is shown, participants attempt to recall its associatively related word from the study list. These associates of “bat” are themselves capable of generating their own associations and these too can be probed experimentally. Attempts to map the associative lexicon of English soon made it clear that some words produce more associates than others. This feature is called *set size* and it indexes a word’s associative dimensionality [18]. Mapping the lexicon also revealed that the associates of some words are more interconnected than others. Some words have many such connections, whereas some have none, and this feature is called *connectivity* [15].

Experiments have consistently shown that the associative strengths between words, the set size, and the connectivity of individual words all have powerful effects upon recall, which existing theories cannot explain. The most generally accepted model uses a Spreading Activation approach, which is based on the idea that activation spreads through a fixed associative network, weakening with conceptual distance (e.g., [4]). Thus,

$$S(t) = \sum_{i=1}^{n} S_{ti}S_{it} + \sum_{i=1}^{n}\sum_{j=1}^{n} S_{ti}S_{ij}S_{jt}, \tag{1}$$

where $S(t)$ is the strength of the activation for a particular target t, given an associative network with n associates, S_{ti} target-to-associate activation strength, S_{it} associate-to-target activation strength (resonance), and S_{ij} associate-to-associate activation strength (connectivity). This model only allows for activation of a target if there are direct links between it and its associates, but there are cases where targets are activated via indirect links [2]. Furthermore, the contextuality of recall is not represented in this model, and yet cuing a word differently changes the relative probabilities of recall.

These problems led to a proposal that word associations be modelled using an equation that is non-directional, that is, the target activates its associative structure in synchrony:

$$S(t) = \sum_{i=1}^{n} S_{ti} + \sum_{i=1}^{n} S_{it} + \sum_{i=1}^{n}\sum_{j=1,i\neq j}^{n} S_{ij}. \tag{2}$$

This equation is termed the Spooky Activation at a Distance equation [15], and it assumes that each link in the associative set contributes additively to the target’s activation strength. The beneficial effects of associate-to-associate links are not contingent on associate-to-target links. Stronger target activation is predicted when there are many associate-to-associate links even when associate-to-target links are absent. In fact, associate-to-target links are not special in any way. Target activation strength is solely determined by the sum of the link strengths within the target's associative set, regardless of origin or direction.

While Eq. (2) shows very good agreement with experimental data its motivation remains unclear. However, it was inspired by the apparent nonlocality of quantum theory; to derive it the "spooky activation at a distance" of quantum theory was assumed to exist for the associative recall of words by humans [15]. Could a more complete quantum model of the human mental lexicon be possible? This paper will explore a new avenue in the modelling of contextual information, suggesting that a model inspired from quantum theory shows some promise for the modelling of the human mental lexicon, and hence the semantics of human language use.

2 Generalising Quantum Theory

QM [quantum mechanics] is actually the answer to a question that was never clearly formulated. We have the answer, what about finding the question?

Philippe Grangier [6]

There is good reason to suppose that a quantum inspired approach can indeed capture contextual information. This section will gradually introduce a model of human word associations, and then examine some recent experimental data suggesting that there is good reason to believe that the human mental lexicon actually exhibits non-separable effects.

2.1 Context, Measurement and Entanglement

Context matters in the formalism of Quantum Theory (QT). From von Neumann's measurement theory and the Heisenberg Uncertainty relations [7], to the more recent Bell and Kochen–Specker theorems [7, 14] the context of a quantum system plays a vital role in the results we obtain from its analysis.

We can quickly see the implicit recognition of context in standard measurement theory as it is developed in textbooks on quantum mechanics. Here, the probability of some measurement outcome is generally extracted from the state function of QT, $|\psi\rangle$, as follows. First, $|\psi\rangle$ is written in terms of a set of basis states, $\{|\phi_i\rangle\}$. This representation of $|\psi\rangle$ is obtained by expanding it as a linear superposition (i.e. an appropriately weighted sum) of one set of basis states (commonly obtained in practice through reference to the *choice* of apparatus and its orientation, state *etc*.). We find that $|\psi\rangle = \sum_i c_i|\phi_i\rangle$ where the weight terms c_i represent the contribution of each component ($|\phi_i\rangle$) of the basis to the actual state. The choice of basis states is governed by the observable to be measured and the quantization procedure that relates each observable, A, to its quantum counterpart, $\hat{A}$ [1, 7]. Perhaps most importantly, the standard interpretation of quantum theory claims that upon measurement the quantum system is found to 'collapse' onto one of the eigenstates associated with the eigenvalue equation $\hat{A}|\psi\rangle = \lambda_i|\psi\rangle$. Hence, a non-linear outcome occurs, which is related to both the state of the system, and to that of the observable. Thus, the quantum formalism incorporates the experimental context of a system into its description of that system, and this context can profoundly affect final outcomes for both the system itself, as well as for the experimental result obtained. This is a highly unusual state of affairs in scientific modelling, which almost by definition assumes that a system of interest can be separated from the models that are used to analyse its behaviour [9]. This contextuality of the quantum formalism is its key feature, and the generalisation of this formalism beyond the physical realm will make it possible to model similar effects in systems not presently well modelled by the scientific method.

This recognition of context allows the quantum formalism to provide a particularly natural model of the uncertainty surrounding cued word recall. This is because the probabilities of QT arise not from a lack of details (as is the case for standard Kolmogorovian probabilities), but rather from the geometrical representation of a state that is implied by this recognition of context. The probabilities of QT are Pythagorean in nature [7], which leads to a remarkably different set of characteristics; they arise from the squaring of quantities that have a phase, and hence can exhibit quite different behaviour when two different quantum states are combined.

In word association experiments, we shall represent the state of a human before they give an answer in a particular experimental setting using a *superposition* state, such as the one appearing in Fig. 1a.

Here, we have the word w, represented in some context c, as a superposition of recalled, $|1\rangle$ and not recalled $|0\rangle$. Thus, the word "bat" might be a target word, expected to be recalled in an extra-list cueing experiment upon presentation of the cue word "cave" which in this case acts as the context c. The probability of "bat" being recalled in this context is represented by a_1^2, as per the measurement postulate of quantum theory [12], but can be easily related to the Pythagorean theorem for the above diagram (which explains its origins). Thus, with reference to the USF word

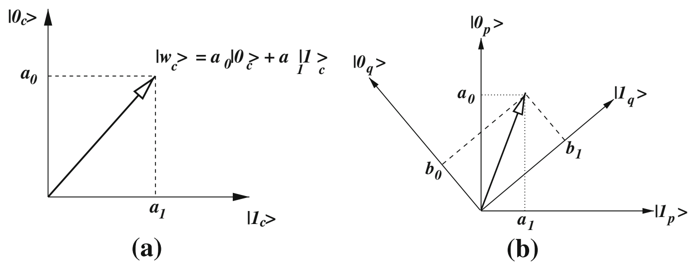


Fig. 1 A concept w, for example *bat*, is represented in some context c which takes the form of a basis. (**a**) The word "bat" is recalled $|1\rangle$, or not, $|0\rangle$, in some context. Thus, if the context is the extra list cue "cave", then the subject might recall "bat" from a prior target list with a probability a_1^2, or they might fail to recall "bat", with the probability a_0^2. Here, as in all quantum superpositions, $a_0^2 + a_1^2 = 1$. (**b**) Changing the cue to "ball" might significantly change the chances of recall

association data [16], we could represent "bat" as the superposition: $\sqrt{0.94}|0\rangle + \sqrt{0.06}|1\rangle$ (see the data available at http://web.usf.edu/FreeAssociation/ for quick access to these numbers) which represents a 6% probability that the word "bat" will be recalled by a subject who is presented with the cue "cave".

This model is made more interesting in Fig. 1b, where we have represented the fact that a different context might result in a different set of recall probabilities. Thus, when given the cue word "ball" we could represent the concept *bat* as the new superposition $\sqrt{0.81}|0\rangle + \sqrt{0.19}|1\rangle$. In this case we see that the word "bat" is more likely to be retrieved from memory when a subject is presented with the cue "ball" than the cue word "cave", which is a very natural outcome. Thus, this formalism provides a natural representation of contextual effects as they actually occur in language.

In addition to this immediate application, the phenomenon of *entanglement* [1, 7, 12] allows us to extend the quantum formalism to the description of systems exhibiting contextual dependencies between one another. If we consider two components $S_{\mathcal{A}}$ and $S_{\mathcal{B}}$ of a system S, then a contextual dependency between the two implies that it is not possible to consider them separately. The quantum formalism provides a very clear description of this state of affairs. If we denote the models of the two components by $|\psi_{\mathcal{A}}\rangle$ and $|\psi_{\mathcal{B}}\rangle$, then a separable combined system, $|\psi_{\mathcal{A}\oplus\mathcal{B}}\rangle$, will be one that can be decomposed using a tensor product: $|\psi_{\mathcal{A}\oplus\mathcal{B}}\rangle = |\psi_{\mathcal{A}}\rangle \otimes |\psi_{\mathcal{B}}\rangle$. In contrast, a system for which the components cannot be considered independently is represented in the quantum formalism using an entangled state. Thus, if for example component $S_{\mathcal{A}}$ always exhibits response a when $S_{\mathcal{B}}$ does, and response b when $S_{\mathcal{B}}$ does then we might represent the combined system as $|\psi_{\mathcal{A}\oplus\mathcal{B}}\rangle = \mathcal{N}_1|aa\rangle + \mathcal{N}_2|bb\rangle$ where $\mathcal{N}_1$ and $\mathcal{N}_2$ take the role of some normalisation factor (i.e. $\mathcal{N}_1^2 + \mathcal{N}_2^2 = 1$). Such a state is impossible to represent as a tensor product, hence it is deemed non-separable, and termed *entangled*.

Returning to the example word "bat" we can recognise that so far, we have represented context into our model through reference to the possible multiple senses of an ambiguous word. We have not as yet considered the interactions between multiple words. For example, what if "bat" was to be considered in the context of a sentence that contained the word "boxer"? Returning to the discussion of Sect. 2.1, we see hope that such interaction might be modelled using entanglement. This argument proceeds as follows.

Both "boxer" and "bat" have animal senses, and sporting senses, and can thus be sensibly represented as recalled, or not, with respect to these contexts. So, if we continue with the context that is suggested by the animal sense of bat, then at least four possibilities arise when a subject is asked to consider the combined system "boxer bat". Firstly, a subject might take a "boxer" to be a dog, hence recalling the animal sense of "boxer", and a "bat" to be an animal. This could be represented as $|11\rangle$. Similarly, a subject might not recall either of these words in the animal sense and this would be represented as $|00\rangle$. However, they might also recall one of the words in an animal sense and the other in the sporting sense, and we could represent these two possibilities as $|01\rangle$ and $|10\rangle$, depending upon which word was recalled in which sense. This list of all four possibilities could be represented as the following state, obtained through use of the tensor product:

$$|boxer\rangle \otimes |bat\rangle = (a_0|0\rangle + a_1|1\rangle) \otimes (b_0|0\rangle + b_1|1\rangle) \tag{3}$$

$$= a_0 b_0|00\rangle + a_1 b_0|10\rangle + a_0 b_1|01\rangle + a_1 b_1|11\rangle, \tag{4}$$

where $|a_0 b_0|^2 + |a_1 b_0|^2 + |a_0 b_1|^2 + |a_1 b_1|^2 = 1$. But it is perhaps more reasonable to assume that not all possibilities are available [2]. For example, it might be the case that either both animal senses are recalled, or neither are recalled, and we would represent this using the entangled state

$$\psi_t = x|00\rangle + y|11\rangle, \text{ where } x^2 + y^2 = 1. \tag{5}$$

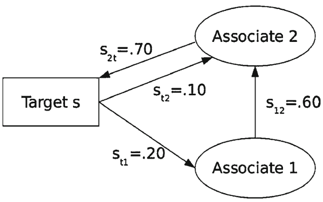
What could such entangled states signify for the human mental lexicon? Essentially, they would account for an ‘all or nothing’ recall [2], where, if one word is recalled then its entire associative network related to that word is also recalled, in contrast to the traditional spreading activation models. This assumption fits with the hypothesis originally made by Nelson and McEvoy [17] that word associations should be activated across an entire associative network, i.e. in synchrony. A comprehensive set of experiments have accumulated data over decades that supports the validity of this hypothesis [2, 15, 18]. Here we shall briefly extend our model to illustrate the manner in which the ‘all or nothing’ hypothesis leads to a toy model that shows some promise in fitting the behaviour of the human mental lexicon.

Figure 2 shows a hypothetical target having two target-to-associate links, it also contains a table listing the association probabilities depicted in this figure, and a set of superposition states that must be somehow combined in a model.

Making use of the ‘all or nothing’ assumption discussed above, we shall choose to model this network as an entangled state,

$$\psi'_t = \sqrt{p_0}|000\rangle + \sqrt{p_1}|111\rangle. \tag{6}$$

This formula expresses a superposed state in which the entire associative structure is either activated $|111\rangle$ or not $|000\rangle$. Choosing the values of the probabilities p_0 and p_1



	t	a_1	a_2
t		0.2	0.1
a_1			0.6
a_2	0.7		
	$p_t = 0.7$	$p_{a_1} = 0.2$	$p_{a_2} = 0.7$

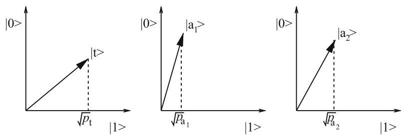


Fig. 2 A hypothetical target with two associates and single associate-to-target and associate-to-associate links. To the *top right*, is a matrix corresponding to hypothetical association network on the *left*. Free associations probabilities are obtained by finding the row of interest (the cue) and running across to the associate word obtained. The corresponding three body quantum system of words is underneath. The projection of the qubit onto the $|1\rangle$ basis relates to the probabilities in the *bottom row* of the table

is problematic, since there is no model of the time evolution for semantic spaces, we are forced to speculate. However, again working with the 'all or nothing' assumption, we could reasonably surmise that the lack of activation of the target is determined solely in terms of lack of recall of any of the associates. That is, $p_0 = \bar{p}_t \bar{p}_{a_1} \bar{p}_{a_2}$. Consequently, the remaining probability mass contributes to the activation of the associative structure as a whole,

$$p_1 = 1 - \bar{p}_t \bar{p}_{a_1} \bar{p}_{a_2} \tag{7}$$

$$= 1 - (1 - p_t)(1 - p_{a_1})(1 - p_{a_2}) \tag{8}$$

$$= \underbrace{p_t + p_{a_1} + p_{a_2}}_{\text{'Spooky'}} + \underbrace{p_t p_{a_1} p_{a_2}}_{\text{'Spreading'}} - \underbrace{(p_t p_{a_1} + p_t p_{a_2} + p_{a_1} p_{a_2})}_{\text{something else}}. \tag{9}$$

Returning to the discussion of Sect. 1, we see that this approach has captured the key features of both the Spreading Activation, and Spooky Action at a Distance equations, a result that is highly promising. In addition, the extra term in this equation suggests that all associates will affect recall, a result that is sympathetic with the decades of experimental data collected by Nelson and McEvoy [15, 18]. Further work is under way to investigate the links between these different equations and the new quantum inspired model. For the present, we note that this form of model can be readily extended to more complicated networks, but there is every chance that the 'all or nothing' assumption is somewhat simplistic. It is possible that different networks will activate in different forms. Thus some word pairs may bias towards anticorrelation (i.e. $x\,|01\rangle + y\,|10\rangle$) or any of the six different entangled states possible. Much work is required for a full model of the human mental lexicon.

For now, we shall ask a related question; is there any reason to believe that word associates might be activated in synchrony? If it were possible to show that words might exhibit entanglement, then Eq. (9) would have some support. In the next section we shall discuss an experiment that gives some preliminary indications that the meanings humans extract from ambiguous words can sometimes exhibit the form of non-separability that is considered by physics to be characteristic of entanglement.

2.2 Violating Bell-Type Tests Using Bi-ambiguous Compounds

In 1964 John Bell constructed an argument that can be used to distinguish between local local hidden variables theories and entangled (i.e. non-separable) systems. The Clauser–Horne–Shimony–Holt (CHSH) inequality provides an experimental realisation of Bell's work. In the basic scenario, a source S emits two entangled photons, one travels left through a polariser at c_A say, and the other photon goes right through a polariser at c_B. The photons can reflect from the polariser, or transmit through it, and the state describing the system becomes more complex again representing the different likelihoods of this occurring. Finally, two detectors in this system 'click', one on the left side, and one on the right. Coincidence is measured in this scenario, with $|11\rangle$ representing a situation where the two detectors requiring transmission through the polariser click, and so on for the other states. Finally, the orientation of these polarisers can be changed, and this leads to a different proportion of photons being transmitted or reflected (see Fig. 3).

The results of this experiment are used to calculate expectation values for the four available combinations of two different polariser settings, a, a', b, b'. In this scenario the expectation value becomes:

$$E(i,j) = \frac{N_{11} + N_{00} - N_{10} - N_{01}}{N_{11} + N_{00} + N_{10} + N_{01}} \text{ where } i \in \{a, a'\}, j \in \{b, b'\}. \tag{10}$$

where N_{11} represents the number of times that $|11\rangle$ occurs, and so on [1, 7]. If the two different sides of this experiment can be considered separately, then the expectation values for this experimental scenario will satisfy the CHSH inequality:

$$-2 \leq E(a,b) - E(a,b') + E(a',b) + E(a',b') \leq 2 \tag{11}$$

which provides us with a numerical test for the separability (or not) of a quantum system. If the system can be considered separable then the CHSH inequality will be satisfied. This then means that it is possible to consider the parts of the system in isolation. Quantum systems can violate Eq. (11) and hence must be considered to be non-separable in at least one, well defined manner.

This section will adapt the basic CHSH experimental scenario in order to test for a similar nonseparability in concept combinations. We shall proceed by returning to the example bi-ambiguous compound "boxer bat".

A "boxer bat" has a number of possible interpretations. It might be construed as "a small furry black animal with boxing gloves on", or perhaps it could be a "baseball bat a boxer dog plays with" etc. In each of these interpretations we see that a different sense of the component concepts has been taken, and this allows us to start talking about outcomes that align with a set of analyser settings $|11\rangle$ say if we choose our experimental arrangement carefully. For a "boxer bat", it is possible to define four primes that perform the role of 'analysers' in four CHSH type experiments. Consider for example the following experimental settings:

1. $(a, b) = (\text{fighter,ball}) \sim (\mathit{sport}, \mathit{sport})$ senses
2. $(a, b') = (\text{fighter,vampire}) \sim (\mathit{sport}, \mathit{animal})$ senses
3. $(a', b) = (\text{dog,ball}) \sim (\mathit{animal}, \mathit{sport})$ senses
4. $(a', b') = (\text{dog,vampire}) \sim (\mathit{animal}, \mathit{animal})$ senses

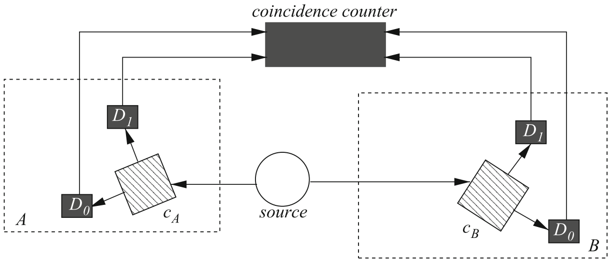


Fig. 3 An experimental scenario testing for the non-separability of an entangled system of polarised photons. A source emits two entangled photons that travel to polarisers at c_A and c_B. In each of the regions A and B, one of the detectors D_0 or D_1 clicks, and this is recorded at a coincidence counter

In this experiment we have chosen to count events as follows; if a subject returns an interpretation for a concept that agrees with the one they were primed with then a $|1\rangle$ will be recorded, if they disagree, then a $|0\rangle$ will be deemed to have occurred. So, if a subject sees the two cues “fighter” and “vampire”, and then deems that a “boxer bat” is “a small furry black animal with boxing gloves on” then they will have scored a $|11\rangle$ and the N_{11} count will be increased, while if they deemed that it was a “baseball bat a boxer dog plays with” then they will have scored a $|00\rangle$, with a corresponding increase in N_{00}.

This reasoning has been followed for a number of different bi-ambiguous concept combinations, resulting in a set of twelve CHSH style pilot experiments. These pilot experiments have been used to explore the structure of the human mental lexicon, and have not been performed with large numbers of participants. Each concept combination had over 40 participants exposed to it, but given the four different experimental arrangements required to construct the inequality this sample size is not large enough to be considered significant as yet. A larger experiment is currently underway.

Table 1 lists all compounds that were tested, along with the words used to define analyser settings (which consist of a word intended to prime a particular word sense). Each compound represents a new experiment, while the senses, which apply to each word in the compound separately, could be regarded as hidden variables. Primes are taken to correspond to polarisers oriented in some particular direction in this scenario.

Participants completed an online experiment in which they were asked to provide an interpretation for twelve compounds (e.g., “boxer bat”). Each compound was seen only once by a participant. For groups 1–8, each compound was preceded by a similarity rating task in which participants rated the similarity between two pairs of words (e.g., “dog” and “boxer”, “vampire” and “bat”) on a 7 point scale (low

Table 1 The compounds chosen for this experiment

Compound	Sense 1 (s1)	Sense 2 (s2)	a (s1)	b (s1)	a′ (s2)	b′ (s2)
Boxer bat	Sport	Animal	Fighter	Ball	Dog	Vampire
Bank log	Natural	Financial	River	Cabin	Money	Journal
Apple chip	Food	Computer	Banana	Potato	Computer	Circuit
Stock tick	Financial	Animal	Shares	Mark	Cow	Flea
Seal pack	Container	Animal	Envelop	Suitcase	Walrus	Leader
Spring plant	Natural	Artefact	Summer	Seed	Coil	Factory
Poker spade	Cards	Implement	Card	Ace	Fire	Shovel
Slug duck	Body action	Animal	Punch	Dodge	Snail	Quack
Club bar	Place	Artefact	Member	Pub	Golf	Handle
Web bug	Insect	Computer	Cob	Beetle	Internet	Computer
Table file	Artefact	Record	Chair	Nail	Chart	Folder
Match bowl	Sport	Artefact	Contest	Throw	Flame	Dish

Each has the same two senses or interpretations, s1 and s2. These compounds are primed by two of four possible cues, each of which biases the compounds towards a certain sense (listed in the table)

Table 2 Expectation values for the experimental settings given in Table 1, along with the value CHSH calculated according to Eq. (11), and CH results calculated according to Eq. (12)

Compound	CHSH	CH
Boxer bat	0.08	−0.67
Bank log	1.92	−0.15
Apple chip	2	−0.09
Stock tick	**2.14**	**0.01**
Seal pack	1.94	−0.03
Spring plant	1.94	−0.07
Poker spade	2	−0.26
Slug duck	**2.04**	−0.46
Club bar	**2.04**	0
Web bug	1.83	−0.11
Table file	−0.09	−0.57
Match bowl	**2.02**	**0.17**

Bolded values indicate non-separable concept combinations

similarity to high similarity). They were then asked to provide an interpretation for a novel compound, and finally, they went through a disambiguation phase when they were required to clarify which sense they used for each word in their interpretation of each word in the compound. This data was collected, and analysed.[1] Full results of this experiment are listed in Table 2, which shows that a violation of the CHSH inequality was found for four bi-ambiguous word pairs ("stock tick", "slug duck", "club bar" and "match bowl".

Thus, we have found some preliminary indications that concept combinations can indeed behave non-separably in some situations. However, we must consider this result in much more detail before we can proclaim success.

Violators of the CHSH inequality do not appear to follow any strong trends. There is a tendency for violations to be recorded in cases where both ambiguous words are interpreted with the same sense (typified by a high expectation value in the (a, b) and (a', b') cue scenarios), but this is not always the case. Certain behaviour must be exhibited by the anti-correlated polarisation cases as well. Examining Eq. (11) suggests a number of plausible violation scenarios constructed around maximal expectation values, but none of our experiments yielded such results. This problem causes us to pause; is the failure to get a strong violation a function of the priming procedure, the experimental procedure, or the human mental lexicon? At present we are unable to answer this question.

It is important to note that our experiment is prone to a detection loophole [1, 11, 12], arising from cases where not all detection events are recorded. Subjects are able to decide that their interpretation fits an "other" category which amounts to an experiment where a detection event is not recorded (see [11] for more details). However, these null cases can be properly considered if we adopt the Clauser–Horne (CH) inequality [3] which incorporates these null coincidences into the violation analysis. The CH inequality uses probability of coincidences, instead of

[1] Full results are available at http://www.quantum-interaction.org/conceptCombinationExpts/data together with the analysis files. Use the login/password pair data/data to view the files.

the expectation values used in (11). Thus, $p(i, j)$ corresponds to the probability that the experiment (i, j) gives the outcome $1, 1 : p(i,j) = N_{11}/(N_{11} + N_{00} + N_{10} + N_{01})$. The CH inequality adds two new experimental arrangements to the CHSH inequality, representing independence-style assumptions corresponding to the probability $p(i)$ that a single wing of the experiment (in region A say) gives the outcome 1 when its analyser is set to experiment (i).

$$-1 \leq p(a,b) - p(a,b') + p(a',b) + p(a',b') - p(a') - p(b) \leq 0 \qquad (12)$$

Thus, this equation takes into account the null detection events on side A and B where a result is not recorded. An analysis using the CH inequality has been performed and the results are reported under the CH column in Table 2. We see that two of the original CHSH violations have been lost due to detection loophole problems, but two violations remain under this analysis ("stock tick" and "match bowl").

These results are only preliminary. Our experiment effectively consisted of 12 separate CHSH experiments and sample sizes are not yet large enough for these results to be considered robust. The choice to perform a number of different scenarios was made in an attempt to cover a wide set of possibilities. The difficulty in mapping the CHSH inequality directly into the case of conceptual combination made it necessary to keep this experiment as broad as possible in order to make the chance of achieving a violation as high as possible. However, a larger data set will be required to strengthen these results, and work is progressing upon this.

A second problem with this data concerns the priming of the different senses of the ambiguous words. The procedure utilised in this experiment was chosen with the expectation that the cognitive task of rating the similarity of the presented words was not too difficult, but that it would cause subjects to think about the ambiguous words forming the compound in a certain context. The presentation of both sets of primes together with their respective ambiguous word on the same page was expected to stop bias between the two 'wings' of the experiment. However, there is reason to believe that this task was not as straight forward as was expected. While the similarity decision was expected to isolate priming to each individual word of the compound (e.g., "ball" primed the sports sense of "bat" and "vampire" primed the animal sense of "bat") this did not always occur [11]. Thus, there is some reason to believe that the priming procedure was not particularly effective in this experiment. Rather than creating the intended entangled state of mind, it may have been distracting subjects from the main task. In fact, a number of participants gave informal feedback saying that they found the similarity rating task to be more difficult than the primary task, and many appeared to be somewhat bemused by this stage of the experiment, which suggests that a task expected to be relatively simple created a heavy cognitive load. This may have led to unexpected outcomes in the experimental results. The new set of data currently being collected eliminates this problem through the use of a simpler priming task.

On a related front, we are not using angles that are necessarily set for for maximal violation [1], hence cannot beyond any doubt expect statistically significant violations. In the physical CHSH experiment, analysers are rotated to a set of maximal angles, and results recorded for each of these settings. The choice of angle is essential to the violations recorded by physics, as not all settings will yield a violation of inequalities (11) and (12). In applying these inequalities to semantic structure we cannot test all 'angles' to find those that exhibit maximal effects. We must find concepts which somehow overlap semantically and then prime them using cue words which bias one of the senses relevant to the compound. There is not as much free choice in determining the 'angles' at which words can be primed.

This problem may be surmountable with an intelligent choice of experiment. In future work we shall utilise a conceptual space approach [5], to find cues and bi-ambiguous words that can be oriented close to predicted maximal violation scenarios. We shall do this by constructing a semantic space from the USF free association norms, and then searching through this space for concepts and primes that have angles between them that are close to the maximal settings. Angles can be found using the vector dot product once the semantic spaces are constructed using standard techniques (see [20, 21] for an introduction to these approaches). If we can find word pairs that should exhibit close to maximal violation theoretically, and then show experimentally that this is indeed the case, then the argument for quantum-like effects in the human mental lexicon will be strong.

One caveat must be mentioned in the interpretation of this result however. If we return to the discussion of Sect. 1, then we see that a violation of CHSH style inequalities may arise due to the inappropriate use of expected values in deriving the inequalities, not to the nonseparable nature of the compounds themselves. While this possible interpretation certainly muddies the claim for quantum-like effects, it does not rule out the overarching result that semantic information is contextual. Either the concept combinations themselves must be considered non-separably, or the compounds in conjunction with their priming words. We consider it likely that both interpretations will be necessary to fully understand the results of these experiments. In any case, all possible interpretations of this data would point to the contextual nature of the human mental lexicon, and to the need for more semantic measures of information.

3 How Much Information is in a Word?

These findings suggest that syntactically separable words must not be considered as separable insofar as their meaning is concerned. Indeed, the meaning extracted from a word will depend heavily upon the other words with which it appears. However, this does not mean that we cannot model the processes by which semantic information is extracted from the human mental lexicon. The discussion of Sect. 2.1 has shown that models of contextuality are indeed possible, and Sect. 2.2 has given us some reasons to believe that these models may indeed be appropriate for the description of the human mental lexicon.

We return to our original topic of information with a question; how much information is in a word? If semantic meaning is indeed contextual in the manner that the experiment of Sect. 2.2 appears to indicate then the idea that a specific measure of information can be attributed to that word is obviously wrong. Indeed, if the sense that a human attributes to a bi-ambiguous word is non-separably related to other words with which it appears, then it is unreasonable to expect that the information content of this word will be adequately represented by an information measure that makes no reference to the context in which that word appears. Shannon-style measures attribute information content to a word in terms of its symbolic representation, not its semantics. We require new, contextual information measures that can capture the semantics of word associations (and the contextual effects of many other complex systems [8]).

The quantum inspired modelling of Sect. 2 opens the way for a provision of these contextualised information measures. Indeed, with models that can discriminate between, and formally address the different forms of contextual dependencies and non-separabilities that arise in the human mental lexicon, we are now in a position where we can indeed start to specify an information measure that takes account of the complex interaction that can be generated between a complex system and the context in which we find it, or even the context in which we create it.

The power of quantum-like approaches appears to lie in their ability to provide both quantitative and qualitative tools for the understanding of exactly these situations of non-separability. While a system might appear to be composed of components that can be considered in isolation, a quantum-like system is distinguished by the contextual and sometimes complementary responses that those parts exhibit to one another, to the environment, and to situations of measurement [10]. This paper has provided one set of examples illustrating the contextual relations that can be exhibited between words, and demonstrating the manner in which this contextuality can then further manifest itself in the meaning that a human subject will extract from from a semantically connected set of words. We think it likely that the future will see the development of far more generalised quantum theories.

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