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# Quantum-like Qualia hypothesis: from Quantum Cognition to Quantum Perception

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33 **Highlights**

34

35 The recent explosion in theories of consciousness, which aim to link subjectivity and physical  
36 substrates, require a better characterization of mathematical structure of quality of consciousness,  
37 or qualia.

38

39 In traditional and intuitive models of qualia, a particular quale is assumed to be a point in a high  
40 dimensional space.

41

42 Such models assume that qualia exist independent of measurements, but they are incompatible  
43 with the findings that qualia are generally affected by measurements.

44

45 To account for how the measurement can affect qualia, a Quantum-like Qualia (QQ) hypothesis  
46 proposes a mathematical structure employed in quantum theory.

47

48 We will outline how QQ can be tested with various experimental paradigms, building on the  
49 successful quantum cognition framework.

50

51

52

53 **Abstract**

54

55 To arbitrate theories of consciousness, scientists need to understand mathematical structures of  
56 quality of consciousness, or qualia. The dominant view regards qualia as points in a dimensional  
57 space. This view implicitly assumes that qualia can be measured without any effects on it. This  
58 contrasts with intuitions and empirical findings to show that by means of internal attention qualia  
59 can change when they are measured. What is a proper mathematical structure for entities that are  
60 affected by the act of measurement? Here we propose the mathematical structure used in  
61 quantum theory, in which we consider qualia as “observables” (i.e., entities that can, in principle,  
62 be observed), sensory inputs and internal attention as “states” that specify the context that a  
63 measurement takes place, and “measurement outcomes” with probabilities that qualia observables  
64 take particular values. Based on this mathematical structure, the Quantum-like Qualia (QQ)  
65 hypothesis proposes that qualia observables interact with the world, as if through an interface of  
66 sensory inputs and internal attention. We argue that this qualia-interface-world scheme has the  
67 same mathematical structure as observables-states-environment in quantum theory. Moreover,  
68 within this structure, the concept of an “measurement instrument” in quantum theory can precisely  
69 model how measurements affect qualia observables and states. We argue that QQ naturally  
70 explains known properties of qualia and predicts that qualia are sometimes indeterminate. Such  
71 predictions can be empirically determined by the presence of order effects or violations of Bell  
72 inequalities. Confirmation of such predictions substantiates our overarching claim that the  
73 mathematical structure of QQ will offer novel insights into the nature of consciousness.

74

75

## 76 1. Introduction

77

78 Research on consciousness has recently entered a new phase. A burst of neuroimaging studies on  
79 consciousness since 1990 has produced a huge amount of empirical data, requiring a principled  
80 explanation for consciousness and its neuronal substrate ([Koch et al., 2016](#); [Mashour et al., 2020](#);  
81 [Seth & Bayne, 2022](#)). Over the last twenty years, many of the initial ideas about consciousness  
82 and brains were abandoned in the face of empirical data. The remaining theories have retained  
83 their core principles in the form of variations that have branched out from these theories. Some  
84 theories aspire to make quantitative predictions, a few of which are currently pitted against each  
85 other in an adversarial way ([Melloni et al., 2021](#)). Through empirical tests of rival theoretical  
86 predictions, substantial scientific progress is to be expected, as has happened in other fields, such  
87 as physics and experimental psychology ([Aspect et al., 1982](#); [Bell, 1964](#); [Einstein et al., 1935](#);  
88 [Freedman & Clauser, 1972](#); [Kahneman, 2003](#)).

89

90 As the science of consciousness matures, it has become increasingly clear that we lack an  
91 understanding of the target phenomenon, namely consciousness. While “consciousness” can  
92 mean the level or presence of consciousness, as in the clinical science of coma, general  
93 anesthesia, or deep sleep ([Casarotto et al., 2016](#)), this article focuses on the issue of quality of  
94 consciousness, feelings of what-it-is-like-to-be, or, in short, qualia ([Balduzzi & Tononi, 2009](#); [Kanai  
95 & Tsuchiya, 2012](#); [Lyre, 2022](#); [Tsuchiya & Saigo, 2021](#); [Tye, 2021](#)). Qualia in consciousness  
96 research comes in two senses, broad and narrow. In the broad sense, we use a quale to mean a  
97 moment of entire conscious experience across all sensory modalities and thoughts, that is,  
98 everything being experienced. Qualia in the narrow sense refers to one aspect of the experience,  
99 such as the “redness” of the sunset, the particular flavor and taste of tuna sashimi, and so on  
100 ([Balduzzi & Tononi, 2009](#); [Kanai & Tsuchiya, 2012](#)). This article embraces both senses of qualia.  
101 What is not qualia concerns everything that is not part of our conscious experience.

102

103 In this article, Section 2 reviews the popular models of qualia and their deficiencies. To address  
104 these deficiencies, Section 3 proposes the Quantum-like Qualia (QQ) hypothesis. Our hypothesis  
105 is inspired by the mathematical structure of quantum theory. None of our claims rests on whether  
106 or not microscopic quantum phenomena play a significant role in the brain and/or consciousness.  
107 Section 4 focuses on empirical research projects that can test the validity of the QQ hypothesis,  
108 followed by the conclusion in Section 5.

109

110

## 111 2. Traditional qualia models and their deficiencies

112

113 Traditional models of qualia are founded on the notion of points in a putative metric space,  
114 sometimes called a psychological space, quality space, qualia space, phenomenal space ([Clark,  
115 2000](#); [Lee, 2021](#); [Rosenthal, 2015](#)) (Figure 1A). These models have been proposed for various  
116 modalities, such as color, time, pain, sound and smell ([Churchland, 2005](#); [Klincewicz, 2011](#); [Kostic,  
117 2012](#); [Renner, n.d.](#); [Shepard & Cooper, 1992](#); [Young et al., 2014](#)). In the cognitive domain, there  
118 are strong arguments that concepts reside in such a space ([Gärdenfors, 2000](#)). Thus it seems  
119 natural to start with the idea to represent qualia as single points in a high dimensional space. Here,  
120 a definite point corresponds to a particular quale (either in the narrow or broad sense). To specify a

121 combination of narrow qualia or a quale in the broad sense, multiple points are often considered as  
122 well<sup>1</sup>.

123  
124 In the case of narrow sense qualia, the distance between the two points relates to the “similarity”  
125 between the respective qualia (e.g., a red quale and an orange quale are close in similarity, but red  
126 and green are dissimilar). Inspired by early work by Shepard, many variants of such similarity  
127 models have been proposed ([Ashby & Perrin, 1988](#); [Krumhansl, 1978](#); [Nosofsky, 1991](#)), where  
128 visualization techniques such as multidimensional scaling ([Borg & Groenen, 2005](#)) have played a  
129 central role (Figure 1A). Under this framework, various types of qualia, e.g., color ([Bujack et al.,  
130 2022](#); [Churchland, 2005](#); [Indow, 1988](#); [Shepard & Cooper, 1992](#); [Zeleznikow-Johnston et al.,  
131 2023](#)), sound ([Cowen et al., 2020](#); [Renner, 2014](#); [Shepard, 1982](#)), object ([Hebart et al., 2020](#)),  
132 emotion ([Cowen & Keltner, 2017](#); [Nummenmaa et al., 2018](#)), olfaction ([Young et al., 2014](#)), art  
133 ([Graham et al., 2010](#)) etc., have been investigated and visualized based on similarity ratings of  
134 pairwise comparisons between the set of qualia under investigation.

135  
136 Despite widespread use, the psychological space approach to modeling qualia encounters three  
137 challenges: the inability to adequately capture indeterminate and dynamic facets of qualia, as well  
138 as their intricate interactions with internal mental processes. The following summary briefly covers  
139 these three points.

140  
141 Firstly, as this approach assumes a quale is a definite entity (e.g., a point or points in a space), it is  
142 unable to capture the intuition that some qualia appear to be indeterminate entities. The  
143 indeterminacy of qualia becomes apparent when one introspects on the border of experience in  
144 space or time or the nature of unattended or barely attended experience. To determine the spatial  
145 border of experience, one can stretch their arms to estimate the limit of the visual field at the  
146 periphery, and experientially confirm that this limit is tenuous. Under complete darkness, it is not  
147 clear that any such boundary exists. Time also seems to have an indeterminate character. The  
148 start and end times of an event often feel unsure and a moment rarely feels point-like, but is  
149 typically experienced as having some duration ([Filk, 2013](#)). Even when one is focally attending to  
150 qualia, one can sense an uncertainty regarding the phenomenal appearance. Changes in certain  
151 aspects of qualia have been psychophysically confirmed. The very act of attending can alter the  
152 quality of the experience ([Carrasco & Barbot, 2019](#)).

153  
154 Qualia can be uncertain in two ways. Firstly, the “epistemic” uncertainty of qualia implies that  
155 qualia themselves are always determinate, i.e., in a definite state, but measurement processes  
156 inject noise so that there is uncertainty about the value of this definite state. Epistemic uncertainty  
157 can be captured by modifying the classical model by replacing a point with a cloud of points.  
158 However, we suspect that some qualia are “ontologically” indeterminate. Such qualia can be  
159 characterized as being in an indefinite “state” whereby properties can only be attributed by means  
160 of measuring an ensemble of like qualia. Consequently, indeterminate qualia cannot be modeled or  
161 represented as a cloud of dots.

162  
163 Secondly, the psychological space approach is by default static and does not account for the  
164 temporal dynamics of qualia, because it maps sensory inputs into qualia “at a given time” (See also  
165 Footnote 1). The temporal dynamics of qualia, however, are one of the most studied aspects of  
166 qualia, from very fine time scales using masking and priming ([Bachmann, 2000](#); [Breitmeyer &](#)

---

<sup>1</sup> Temporally extended and varying qualia can be represented as either a dynamically moving single point in high-dimensional space or a single point of a very high-dimensional space, where different time points are represented as different dimensions.

167 [Ogmen, 2007](#)), to larger time scales involving adaptation, expectation ([Melloni et al., 2011](#)), and  
168 multistability ([Brascamp et al., 2018](#); [Maier et al., 2012](#)). If the space itself changes dynamically,  
169 the traditional psychological space approach may require substantial updates to account for the  
170 spatio-temporal dynamics of qualia.

171  
172 Thirdly, the psychological space approach is not well developed regarding how qualia interact with  
173 internal mental processes, such as attention. As alluded to above, how we attend to sensory inputs  
174 appears to significantly alter what we experience ([Carrasco & Barbot, 2019](#)), as implied from  
175 change blindness and inattention blindness demonstrations ([Pitts et al., 2018](#); [Simons & Rensink,  
176 2005](#)). However, before we pay attention, we already experience something at the to-be-attended  
177 locations, and that is the reason why we can consciously direct attention there. The psychological  
178 space model is similarly unclear about how qualia relate to other internal processes, such as  
179 memory and expectation.

180  
181 Of course, any general framework can be in principle extended. Yet, since the pioneering work by  
182 Shepard ([Shepard, 1970, 1962b, 1962a, 1980, 1987](#)), subsequent extensions (e.g., concerning  
183 dynamics) have not been proposed. It is noteworthy that masking effects have been documented  
184 for over a century ([Breitmeyer & Ogmen, 2007](#); [Exner, 1868](#)), and despite more than six decades  
185 of exploration within high dimensional point models, scant insights into these effects have  
186 emerged. We contend that the outlined QQ hypothesis presented here holds promise for  
187 explicating such masking phenomena, even without properly fleshed out computational models<sup>2</sup>.

188  
189 Thus, the psychological space approach to modeling qualia as points in a dimensional space  
190 appears deficient in regard to psychophysically-informed intuitions that qualia are indeterminate,  
191 dynamic, and interact with other mental processes. But why do researchers continue to adhere to  
192 the psychological-space models? We surmise that this is due to the combination of the intuitive  
193 appeal of such models and the lack of compelling alternatives<sup>3</sup>.

194  
195 Interestingly, a similar situation arose in the field of cognitive science, in particular decision making.  
196 In decision making, models based on standard probability theory and logic have been persistently  
197 challenged by many (apparently) paradoxical findings in human decision making. Some of these  
198 paradoxes in decision making have had fairly natural explanations by means of quantum  
199 probability theory, which was introduced in psychology with the quantum cognition framework  
200 ([Busemeyer & Bruza, 2012](#); [Haven & Khrennikov, 2013](#); [A. Y. Khrennikov, 2010](#); [Pothos &  
201 Busemeyer, 2022](#))<sup>4</sup>. Notably, analogous qualia-related concerns have been raised in the context of

---

<sup>2</sup> One promising venue is dynamical models of consciousness and qualia ([Esteban et al., 2018](#);  
[Fekete & Edelman, 2011](#); [Moyal et al., 2020](#)). However, so far, such models do not address the  
issue of how measurements and observations affect qualia, one of the central points of our paper.

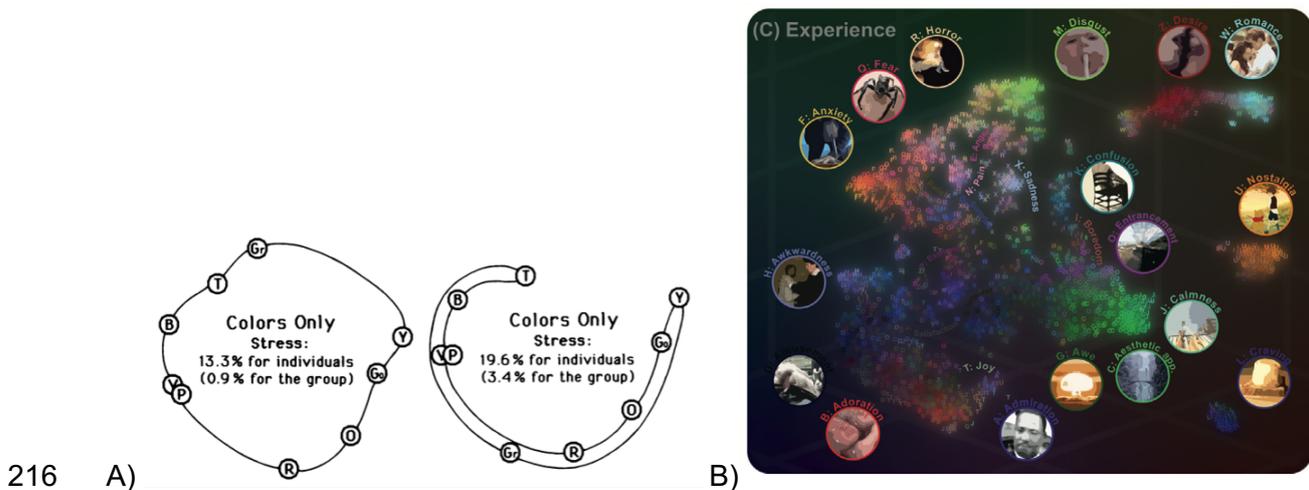
<sup>3</sup> For more recent mathematically elaborated models, see ([Hoffman et al., 2023](#); [Kleiner, 2024](#);  
[Kleiner & Ludwig, 2024](#)) and references therein.

<sup>4</sup> Some studies in quantum cognition are highly relevant to our proposal ([Atmanspacher & Müller-  
Herold, 2016](#); [Filk, 2009](#); [A. Khrennikov, 2015, 2021](#)). Our Quantum-like Qualia (QQ) hypothesis is  
quite orthogonal to the Quantum Brain hypothesis, which considers quantum mechanical  
processes in the brain ([Hameroff & Penrose, 2014](#)) and the role of consciousness in quantum  
collapse ([Chalmers & McQueen, 2021](#)) (See also ([Smolin, 2022](#))). QQ is completely consistent  
with the possibility that all physical events happening in the brain are purely classical. Our core  
idea is to utilize the mathematical formalism of quantum theory, as outlined below. For these and  
other related issues see ([Atmanspacher, 2017](#)).

202 human decision-making. By incorporating the indeterminacy inherent in quantum theory and  
 203 acknowledging the role of measurement in determining the state within cognitive processes, it has  
 204 become possible to more effectively model these phenomena, propelling the growth of the  
 205 quantum cognition field. Consequently, we posit that quantum cognition establishes the conceptual  
 206 and theoretical foundation of the Quantum-like Qualia hypothesis.

207  
 208 Decision making and other cognitive processes are inextricably linked to perception and sensation  
 209 ([Barsalou, 2010](#)) and also appear to share basic neural processing architectures. Thus, it seems  
 210 natural to consider the application of quantum probability theory as an alternate mathematical  
 211 framework for qualia, in order to address the challenges for the psychological space approach.

212  
 213  
 214  
 215



217 **Figure 1. Traditional psychological space models.**

218 Traditional psychological space models ([Lee, 2021](#); [Rosenthal, 2015](#); [Shepard & Cooper, 1992](#))  
 219 assume each quale occupies a point in space (or a combination of points). “Distances” between  
 220 two points are assumed to be related to perceived experiential similarity ([Ashby & Perrin, 1988](#);  
 221 [Krumhansl, 1978](#); [Nosofsky, 1991](#)). A) A classic color hue ring model for the representation of  
 222 similarity relationships among 9 colors for color-typical and red-green color blind individuals  
 223 ([Shepard & Cooper, 1992](#)). B) Similar representations (points-in-high dimensional spaces) have  
 224 been used in other domains of experience, such as emotional experience ([Cowen & Keltner,](#)  
 225 [2017](#)). Here, 2185 brief videos are represented as points using the tSNE algorithm ([van der](#)  
 226 [Maaten & Hinton, 2008](#)).

227

228

229

230

### 231 3. The Quantum-like Qualia hypothesis

232

233 Three essential challenges for existing models for qualia (i.e., indeterminacy, dynamics, and  
 234 interactions) are inherently related with the limitations in “classical” approaches. Classical  
 235 approaches assume that qualia can be probed, observed, reported or “measured,” without  
 236 affecting them. To consider a more general mathematical structure, it is useful to start with the

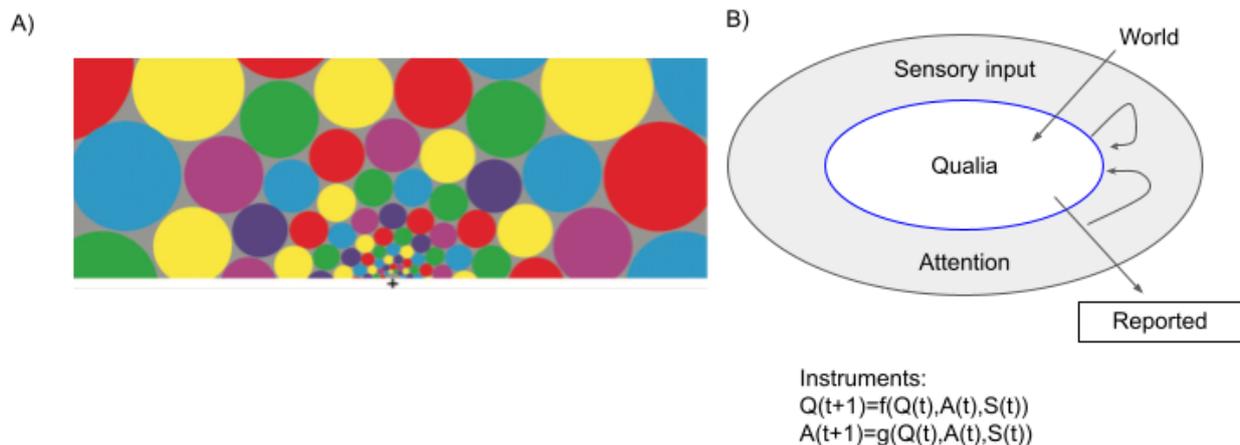
237 assumption that such “measurements” necessarily affect qualia. How much these measurements  
238 affect qualia can vary depending on various factors.

239  
240 Quantum theory offers a mathematical structure that deals with entities whose properties can  
241 change upon measurement. As we argue below, such a mathematical structure, proposed as a  
242 Quantum-like Qualia (QQ<sup>5</sup>) hypothesis, attains the three desired features for qualia. QQ states that  
243 qualia are like quantum entities, which are inextricably affected by measurement. We first give a  
244 broad sketch of QQ (Figure 2), then explain technical concepts with familiar examples from  
245 consciousness research. More detailed mathematical formulations will be pursued in future work.

### 246 247 **3.1 Separating qualia observables from states (of sensory input and attention)**

248  
249 To account for the indeterminacy of qualia, QQ distinguishes each instance of measured value of  
250 qualia (say, color qualia Q=“red”) from all possible measurable qualia. Inspired by quantum theory,  
251 we call all possible measured outcomes “observables”. Observables are intrinsic properties of a  
252 system that can, in principle, be measured. For example, a color qualia observable at the fixation  
253 can be a coarse set of color labels, such as Q={“red”, “blue”, “green”, ...}. QQ does not presuppose  
254 that all aspects of qualia can be simultaneously measured and reported<sup>6</sup>.

255  
256 Now consider a situation where you momentarily see many color patches (Figure 2A). Suppose  
257 you are attending to the right most red patch. This kind of “sensory input” and “attention” constitute  
258 a “state”, separate from “observables”. While each color quale can be indeterminate, under a  
259 particular “state”, the expected value of a particular quale (modeled as an observable) is a given.  
260 Formally, states are like functions that return the expected value for a given quale, when a  
261 particular observable is measured.  
262



263

264 **Figure 2. Conceptual framework of the QQ hypothesis.**

265 A) An exemplar sensory input of many colorful patches with the size of each patch proportional to  
266 cortical magnification (Tyler, 2015). While you are fixating on the cross at the bottom center, you  
267 see the color of each patch without moving your eyes. However, you may feel your experience  
268 changes depending on where you direct your attention. B) The conceptual diagram of QQ. QQ

<sup>5</sup> This is different from the quantum question (QQ) equality by Wang and Busemeyer (Z. Wang et al., 2014).

<sup>6</sup> Note this statement is about measurement and reports on qualia. We assume that qualia exist before measurements in the same way quantum particles exist before measurement.

269 considers Qualia as observables that are properties of a system that can be in principle  
270 “measured”, probed and reported. Sensory inputs and Attention act as an interface or a “state”  
271 between Qualia and the World. For example, here the state can be “the sensory input as in (A)  
272 AND attending to a red patch on the right”. Then, we can define and measure a probability that a  
273 particular value is assigned to the observable, for example,  $\text{Prob}(\text{“color Q for the leftmost circle”} =$   
274  $\text{“blue”} \mid \text{the state}) = 0.7$ . How Qualia (Q), Attention (A) and Sensory input (S) evolve over time with  
275 or without measurement is formalized by the theory of Instruments ([Davies & Lewis, 1970](#); [Ozawa](#)  
276 [& Khrennikov, 2021](#)). Informally, the putative interaction between the world and qualia, qualia and  
277 subjective reports, and how reports alter attention and qualia through instruments are depicted by  
278 arrows in the panel.  
279

280  
281

### 282 **3.2 Dynamics of qualia observables and states: updates through instruments**

283

284 In quantum theory, there are three mathematically equivalent ways to consider the dynamics of  
285 observables and states ([Sakurai & Napolitano, 2014](#)) (See Table 1 for a summary). QQ considers  
286 both observables and states to change over time. This interpretation is called an “interaction”  
287 picture.  
288

289

289 In most quantum cognition studies, observables are possible response options, which are fixed,  
290 while (mental) states change dynamically. This idea of fixed-observables and dynamic-states is  
291 called the “Schrödinger” picture. In QQ, we consider sensory inputs and attention as “states”. It is  
292 not difficult to imagine how these “states” can change measurement outcomes.  
293

294

294 In some fields of physics (e.g., particle physics), states are considered to be fixed, while  
295 observables change. This dynamic is called the “Heisenberg” picture. In QQ, it is natural to  
296 consider changes of qualia observables as a consequence of changes in the brain through  
297 perceptual learning, sensory adaptation, and so on ([C. Song et al., 2017](#)). In this case, even if  
298 sensory inputs and attention are fixed, qualia can change.  
299

300

300 In this paper, we predominantly consider sensory inputs and internal attention as major  
301 foundational elements of states, but other mental elements, such as memories and expectations,  
302 can also constitute states. Thus, in this interaction picture, QQ explicitly considers how qualia  
303 (observables) interact with states (sensory inputs and attention). Without a state, we cannot  
304 consider a particular measurement outcome of any qualia observable.  
305

306

306 Finally, to formalize how qualia observables interact with other mental processes, we introduce the  
307 concept of an “instrument” (cf. the arrows in Figure 2; [Davies & Lewis, 1970](#)). In modern  
308 measurement theory, any measurement of the system is described by a mathematical structure  
309 called a (measurement) instrument, which offers a generalization of a conditional probability. In  
310 standard quantum physics, measurements are considered all-or-nothing. As the theory of quantum  
311 measurement matured, researchers arrived at the concept of instruments as the most general form  
312 of measurement. The formalism of instruments offers a bridge from nonlinear wave collapse (which  
313 is the result of a measurement in standard quantum theory) to the unitary dynamics of an isolated  
314 system and ‘unsharp’ or weak measurements. We propose that this generalized formalism to  
315 characterize the effects of measurements would be particularly useful when considering the  
316 interaction between qualia and attention. Attention may not determine qualia in an all-or-nothing  
317 way, but rather in an unsharp or weak way.  
318

319 Instruments are utilized in modern quantum measurement theory and have started being applied in  
320 the field of quantum cognition ([A. Khrennikov, 2015](#); [Ozawa & Khrennikov, 2021](#)). Instruments can  
321 describe how qualia observables and states of sensory inputs and attention dynamically develop  
322 upon measurements.

323  
324 While the above descriptions are sufficient to understand the foundations of the QQ hypothesis, we  
325 now expand the conceptual framework and provide associated technical details.

### 326 **3.3 What counts as a system?**

327  
328 We define qualia observables as all possible intrinsic properties of a system. But what is meant by  
329 the term “system”? We consider a system minimally as “that which is experiencing the qualia in  
330 question”. It would correspond to “the complex” in Integrated Information Theory ([Albantakis et al.,  
331 2022](#)). Over time, a system itself can change (then observables would change accordingly). Yet  
332 the system should still need to be identified as a coherent entity or phenomenon. A system has an  
333 associated set of qualia observables, which can be measured from the outside environment.

### 334 **3.4 A state as an interface between qualia and the world**

335  
336 The interrelationship between the system and the environment external to it is represented by the  
337 state of the system. In a sense, a state can be considered an interface. This idea may sound  
338 strange at first, but actually it is equally applicable across classical and quantum theory ([Ojima,  
339 2004](#); [Saigo, 2021](#); [Saigo et al., 2019](#)). For example, the temperature of water in a cup as an  
340 observable needs to be determined in the context (= “state”) of where and how the measurement  
341 instruments are placed<sup>7</sup>.

342  
343 In QQ, such a context would involve at least sensory inputs and attention. In a particular state, call  
344 it “ $\varphi$ ”, the expected value of reporting a particular quale,  $P(Q=q|\varphi)$  can be established. For  
345 example, in a state  $\varphi$  = “one is sitting at the sunset with the mind wandering”,  $P(Q=$ “seeing the  
346 color of red” |  $\varphi)$  can be established. Or, in a state  $\varphi$  = “sensory input to a participant is a weak  
347 grating stimulus with masking under a particular attentional instruction”, we may obtain  $P(Q=$ “faint”  
348 |  $\varphi) = 0.7$ , when we assume  $Q$  as observables with outcomes of {highly visible, less visible, faint,  
349 not visible}. Note that in this framework, there is no point in talking about considering a single-trial  
350 quale as in [ $Q=$ “faint”] without considering the state. We can consider only an ensemble of  
351 measurement outcomes given a particular state.

352  
353 The notion of an interface between system and environment is an important idea, as discussed in  
354 many theories of consciousness. Just to name a few, “interface” in interface theory of  
355 consciousness ([Hoffman et al., 2015, 2023](#); [Prakash et al., 2020](#); [Prentner, 2021](#)), “background  
356 conditions” in the Integrated Information Theory of consciousness, [Albantakis et al., 2022](#), “Markov  
357 blanket” in the free energy principle, [Kirchhoff et al., 2018](#), and “mediation” in philosophy, ([Taguchi,  
358 2019](#)).

---

<sup>7</sup> Consider all possible temperatures of water as observables. The temperature of water is a complex physical concept, which depends not only on the average kinetic energy of water molecules but also on the measuring probe device’s temperature, surface areas, and many other factors. We treat all of these factors that relate to measurement as “states”. In the case of measuring water temperature, depending on how invasive the measurement probe is (with a probe from either a very cold or very hot environment), the measured outcome of the temperature of water can change.

361  
362 Inspired by the mathematical structure of quantum theory, QQ aspires to establish principled  
363 associations among observables, states, and their interactions, not at the level of an individual  
364 event (or the qualia property at each moment) but at the level of collections of similar events. In  
365 fact, for every individual event, the set of all qualia properties would be unique and never identical  
366 to the other sets, especially when space and time are considered. Thus, QQ proposes that qualia  
367 should not be considered at the level that assumes definiteness of qualia properties for each event.  
368 Rather, QQ proposes to consider qualia at the level of ensembles where some “similar” qualia  
369 properties are grouped together (as in the above categorical set of observables). How to construe  
370 “similar” is an important question, which the authors have discussed elsewhere, using concepts  
371 from category theory ([Tsuchiya et al., 2016, 2022, 2023](#)). In category theory, it is quite explicit what  
372 one considers as similar is a choice of mathematicians or scientists, not automatically or uniquely  
373 ‘given’ by the world ([Cheng, 2022](#)). In most theoretical and experimental contexts, qualia are  
374 similar as long as they are considered similar in some way by the observing individual, as in the  
375 everyday usage of “similar”.

376  
377 In summary, “state” is an interface that assigns an “average” value to each observable, noting that  
378 measurement of a single event may not be possible.

### 379 **3.5 Instrument formalism for dynamics of qualia and states**

381  
382 Let us now consider the dynamics of qualia. For simplicity, in relation to a discrete time step,  
383 denote qualia, sensory input, and attention at time  $t$  as  $Q(t)$ ,  $S(t)$ , and  $A(t)$ . Their interdependency is  
384 illustrated by the arrows in Figure 2. The dynamical update rules are expressed as

385  
386  $Q(t+1) = f(Q(t), S(t), A(t))$  and  
387  $A(t+1) = g(Q(t), S(t), A(t))$

388  
389 This simple formulation is a primitive form of an instrument. Currently, we do not have enough data  
390 to constrain the form of the functions  $f$  and  $g$ . However the equations generally formalize how  
391 changes of sensory inputs<sup>8</sup> affect both what we experience and how we attend. They also capture  
392 how attending to uncertain aspects of qualia (e.g., a spatial boundary) can change qualia. For  
393 specific and empirical applications of instruments in quantum cognition, see ([Ozawa & Khrennikov, 2021](#)).

### 394 395 396 **3.6 A common mathematical and philosophical structure between quantum phenomena and qualia**

397  
398  
399 QQ proposes an application of some aspects of the mathematical structure from quantum theory  
400 (e.g., separation of observables, states and averaged measured outcomes, and instruments). In  
401 parallel with the mathematical structure, we surmise that there is a common philosophical stance  
402 covering both quantum phenomena and qualia. Through such a philosophical connection, QQ  
403 naturally situates some of the perplexing psychological findings in qualia and attention as detailed  
404 below.

---

<sup>8</sup> While some theories consider a possible role of conscious agents on the control of  $S(t+1)$  through motor control and intention, we consider that they are better left out from the formalism of this update rule of instrument for qualia. Consider the sensory input while you are looking at an ever-changing shape and colors of a burning fireplace. Also, in an experimental situation, experimenters can change sensory input  $S(t+1)$  to a participant in any way they want.

405 **3.6.1 Noncommutativity, complementarity, uncertainty relations in quantum theory, quantum**  
406 **cognition and QQ**  
407

408 One of the foundational ideas behind quantum theory is “complementarity”. In the context of qualia,  
409 two qualia are complementary when they cannot be experienced simultaneously, as we consider in  
410 more detail below ([Bruza et al., 2023](#))<sup>9</sup>. Complementarity is a philosophical concept that one of the  
411 founders of quantum theory, Niels Bohr, introduced in physics, indirectly inspired by one of the  
412 founders of modern experimental psychology, William James, through Edgar Rubin ([Holton, 1988](#)).  
413

414 The idea of complementarity can be mathematically expressed via the concept of  
415 noncommutativity ([Atmanspacher & Filk, 2018](#); [Streater, 2007](#)). Noncommutativity implies  
416 sensitivity to the order of an operation. In general, the effect of processing A then B may not be the  
417 same as B then A. Noncommutativity is the default for many processes, from cooking to chemical  
418 reactions<sup>10</sup>. In the brain, this could correspond to the effect of processing A leaving some trace, in  
419 terms of synaptic plasticity or neuronal activity, which impacts on processing B. If this is the case,  
420 processes A and B are expected to be noncommutative and likewise for the corresponding qualia.  
421

422 If observables A and B are noncommutative, measuring A after B typically yields a different  
423 outcome to B after A. It is generally accepted that many aspects of human cognition are  
424 noncommutative. Even in arithmetic, subtraction and division are noncommutative. Whilst  
425 multiplication is commutative for numbers, it is not for matrices. Note that matrix operations are  
426 fundamental to quantum theory ([Busemeyer & Bruza, 2012](#)). Noncommutative observables can be  
427 used to formalize important features of qualia, such as the aforementioned indeterminacy. Starting  
428 with the well established noncommutative formalization of quantum theory as a guiding framework,  
429 it should be possible to appropriately extend this formalism for QQ and, as we explain later, it  
430 should be possible to empirically demonstrate its necessity.  
431

432 Regarding qualia, in general, when we consider “processes”, whereby the order of the processes  
433 matters. In an example drawn from masking, presenting target T briefly before mask M at a  
434 particular interval can make T completely invisible. But swapping the order into M then T, both of  
435 them can become highly visible. This is an example of noncommutativity. Quantitative and  
436 coherent explanations of order effects, fallacies in decision making, conceptual combination,  
437 evidence accumulation, over/under distribution effects in memory and other cognitive phenomena  
438 is one of the hallmarks of the quantum cognition framework ([Busemeyer & Bruza, 2012](#);  
439 [Busemeyer & Wang, 2017](#); [Pothos & Busemeyer, 2022](#)). Complementarity as noncommutativity is  
440 experimentally demonstrated as uncertainty relations ([Atmanspacher & Filk, 2018](#)).  
441

442 Complementarity, noncommutativity and uncertainty relations are the basis of quantum theory,  
443 from which the field of quantum cognition arose. Quantum cognition started from explaining  
444 enigmatic phenomena in decision making ([Aerts et al., 2018](#); [Basieva et al., 2019](#); [Broekaert et al.,](#)  
445 [2020](#); [Busemeyer et al., 2019](#); [Mistry et al., 2018](#)), concept combination ([Aerts & Arguëlles, 2022](#);  
446 [Bruza et al., 2015](#); [D. Wang et al., 2021](#)), and judgment ([Ozawa & Khrennikov, 2021](#); [Z. Wang &](#)  
447 [Busemeyer, 2013](#); [White et al., 2020](#)). It has recently expanded into modeling for language ([Surov](#)

---

<sup>9</sup> Note that we are not saying that all qualia are complementary to each other. Some combinations of qualia are likely to be complementary and cannot be experienced at the same time. Indeed, at each moment, we are experiencing multiple qualia at the same time. This is consistent with our introduction of a concept of “broad-sense” qualia. A broad-sense quale is composed of qualia in narrow sense in a unified way.

<sup>10</sup> Note that non-commutativity includes commutativity as a special case. This is similar to the statement that quantum probability theory includes classical probability theory as a special case.

448 [et al., 2021](#)), emotion ([Huang et al., 2022](#); [Khrennikov, 2021](#)), music ([beim Graben & Blutner,](#)  
449 [2019](#)), and social judgments ([Tesař, 2020](#)). It is beginning to be applied to solve real-world  
450 problems ([Arguëlles, 2018](#); [Q. Song et al., 2022](#); [Wojciechowski et al., 2022](#)) and it has been  
451 influencing the design of artificial intelligence and robots that aim to interact with the world ([Ho &](#)  
452 [Hoorn, 2022](#)).

453  
454 To the extent that cognition is continuous with perception ([Barsalou, 2010](#)), quantum cognition is a  
455 relevant framework to consider quality of perceptual consciousness, or qualia. Indeed, certain  
456 applications of quantum cognition to perceptual judgements are already emerging ([Asano et al.,](#)  
457 [2014](#); [Atmanspacher & Filk, 2010](#); [Bruza et al., 2023](#); [Conte et al., 2009](#); [Epping et al., 2023](#);  
458 [Yearsley et al., 2022](#)) as we will discuss below.

459

### 460 **3.6.2 A common philosophical structure between quantum phenomena and qualia**

461

462 On the philosophical side, both quantum phenomena and qualia arise from “interactions”. In the  
463 above, we introduced “a state as an interface”, which is an idea almost equivalent to the  
464 philosophical concept of “mediation” ([Taguchi, 2019](#)). Quantum phenomena arise from interactions  
465 between quantum objects, such as photons, and measurement devices ([Plotnitsky, 2021](#)).

466

467 Notably, Niels Bohr stated that the “reality” responsible for quantum phenomena is indeterminate  
468 and beyond representation ([Plotnitsky, 2021](#)). By “reality”, we mean a definite single event before  
469 any measurement. Such a concept is not problematic in the classical view, which assumes that  
470 anything can exist before measurement and it is in principle not affected by measurement. In  
471 quantum theory, a property of an observable is not defined without a state and there is no meaning  
472 to a single measurement outcome. In this sense, we adopt a view analogous to Bohr’s that “reality”  
473 is “indeterminate” and “beyond representation” before any measurement.

474

475 Likewise, QQ proposes that the reality of qualia defies concrete representation in a similar way,  
476 such as points in a high dimensional space in classical models. Note that classical models can  
477 consider a distribution of points rather than a single point. However, this still assumes the  
478 existence of “reality” of qualia before measurement. Moreover, measurement is assumed to  
479 introduce noise so that a probability distribution is needed to model it. In this view, the underlying  
480 uncertainty is epistemic due to the limitation of our measurement technique or lack of knowledge.  
481 However, QQ proposes that measurement outcomes statistically arise from interrelationship  
482 between qualia observables and states of sensory inputs and attention. In other words, the  
483 underlying uncertainty of qualia is ontic due to the nature of the very “being-ness” of qualia  
484 phenomena. If qualia are ontologically uncertain, we would be unable to establish what property  
485 each qualia observable corresponds to, for at least some states at a single event, even if we had  
486 all relevant information available<sup>11</sup>. For such qualia, the act of measurement does not reveal pre-

---

<sup>11</sup> As “ontologically” indeterminate qualia, we consider several cases where measurements of qualia have non-ignorable impacts (periphery, similarity judgements, attention related experiments). In Section 4, we provided empirical experiments to address this issue. In classical physics objects exist independent of measurement. Similarly, classical qualia models tend to assume existence of qualia independent of measurement. For example, in encountering an unfamiliar painting, classical models tend to assume that you have some preference even if you do not articulate it or even if it is uncertain. Our QQ is more explicit about this. Some qualia are affected by measurement and measurement instrument theory (in the future) should specify how a particular type of measurement should affect qualia in what way. This also means that QQ also anticipates some qualia are not affected by measurements as well (say, the color of apple in front of you).

487 existing properties of qualia observables. Rather the measured property emerges as part of the  
488 interrelationship between qualia observables and a state where a measurement takes place.

489  
490 In classical philosophy literature, representationalism states that the phenomenal character of  
491 experience is reducible to representational content ([Block, 1998](#)). These views typically conceive of  
492 a definitive single event, regardless of a state, which is reduced to a cognitive representation. By  
493 contrast, anti-representational views of consciousness propose that such a definitive  
494 representation does not exist ([Gibson, 2014](#); [Koenderink, 2010](#); [Schlicht & Starzak, 2021](#); [Varela,  
495 Francisco et al., 2017](#)). While the precise reasoning behind the latter views is not the same, the  
496 QQ hypothesis shares the same conclusion.

497  
498 The point of quantum theory, as argued by Bohr, is to abandon the assumption that “reality” must  
499 be definitive and to argue that, due to indeterminacy, the underlying “reality” cannot be represented  
500 in a classical way. Instead, quantum theory offers a suitable predictive and explanatory framework.

501  
502 The analogy with qualia is that, due to their indeterminacy, some qualia cannot be “represented” as  
503 points in the dimensional space, as is usually assumed. Specifically, QQ points out that at least  
504 some qualia are indeterminate when they are in an unattended state. In many cases, when  
505 attention is directed to a particular qualia observable, measurement outcomes about the attended  
506 property would become more determinate. This corresponds to an intentional, content-bearing  
507 phenomenal object with an associated cognitive representation as proposed by the orthodox  
508 cognitive science. However, in an unattended state, these qualia observables have properties,  
509 which do not have well established values or qualities. Classical representationalism does not  
510 consider such a possibility. Further, as we elaborate later, QQ predicts that the measurement  
511 outcomes are not only statistical but they additionally violate some statistical laws that must be  
512 satisfied if qualia properties are always determinate.

### 513 514 515 **3.7 Interim summary: What is the Quantum-like Qualia hypothesis?**

516  
517 In summary, QQ hypothesizes the following. First, observables correspond to all possible aspects  
518 of experience that a system can have, including experiences from all sensory modalities, as well as  
519 thoughts, concepts, memories and feelings, that is, anything, as long as it is part of an experience  
520 (i.e., qualia in the broad sense). States are a particular arrangement of the system. When the  
521 system is in a given state, averaged measurement outcomes from qualia observables can be  
522 lawfully specified. States represent sensory inputs and any internal condition of the system,  
523 including how the system attends to or accesses observables. Second, averaged measurement  
524 outcomes are results of interactions between observables and states and they can be reported  
525 outside the system. Third, observables and states change dynamically and interact with each  
526 other, as formalized by the instrument theory. From mathematical and philosophical perspectives,  
527 qualia have an analogical correspondence with quantum phenomena. Table 1 summarizes these  
528 basic concepts and how they are used in quantum theory, quantum cognition, and QQ.

529  
530

	Observables	States	Averaged measurement outcomes
Quantum Theory	$\mathcal{A}$	$\Psi$	$\Psi(a), a \in \mathcal{A}$
Quantum Cognition	Response options (fixed)	Mental states (dynamic)	Responses
Quantum-like Qualia	Qualia (dynamic)	Sensory inputs, attention (dynamic)	Reportable aspects of qualia

531  
532  
533  
534  
535  
536  
537

**Table 1. Conceptual summary of quantum terminologies (columns: observables, states, averaged measurement outcomes) and how they are used in (rows) quantum theory, quantum cognition, and QQ (the Quantum-like Qualia hypothesis). Each cell entry explains a representative usage of each concept.**

#### 538 **4. What are the benefits of QQ and how can we test QQ predictions?**

539

540 As explained above, QQ accords with fundamental intuitions about qualia, such as their  
541 indeterminacy, dynamics, and interaction with internal processes. Furthermore, QQ offers some  
542 important insights concerning our empirical knowledge about qualia and provides novel  
543 perspectives about the nature of qualia. Here we provide some details of three lines of  
544 investigation comprising order effects, violation of the Bell inequality, and relationships between  
545 qualia and attention, thereby showcasing how to empirically test various predictions from QQ.

546

##### 547 **4.1 Order effects in similarity judgments among color qualia.**

548

549 The QQ hypothesis is empirically testable in surprisingly simple ways. One way is to ask if the  
550 order of questions or stimuli matters for the resulting reports. Epping and colleagues ([Epping et al., 2023](#))  
551 presented a pair of color patches to participants, then asked if the reported similarities are  
552 symmetric with respect to the order of color patch presentation.

553

554 Since seminal work by Rosch ([Rosch, 1975](#)) and Tversky ([Tversky, 1977](#)), perceptual similarity  
555 judgments about colors, faces and objects have been repeatedly shown to be asymmetric ([Best &  
556 Goldstone, 2019](#); [Hodgetts & Hahn, 2012](#); [Polk et al., 2002](#); [Roberson et al., 2007](#)). These studies  
557 challenge standard points-in-space type models, requiring arguably ad hoc modifications ([Ashby &  
558 Perrin, 1988](#); [Krumhansl, 1978](#); [Nosofsky, 1991](#)).

559

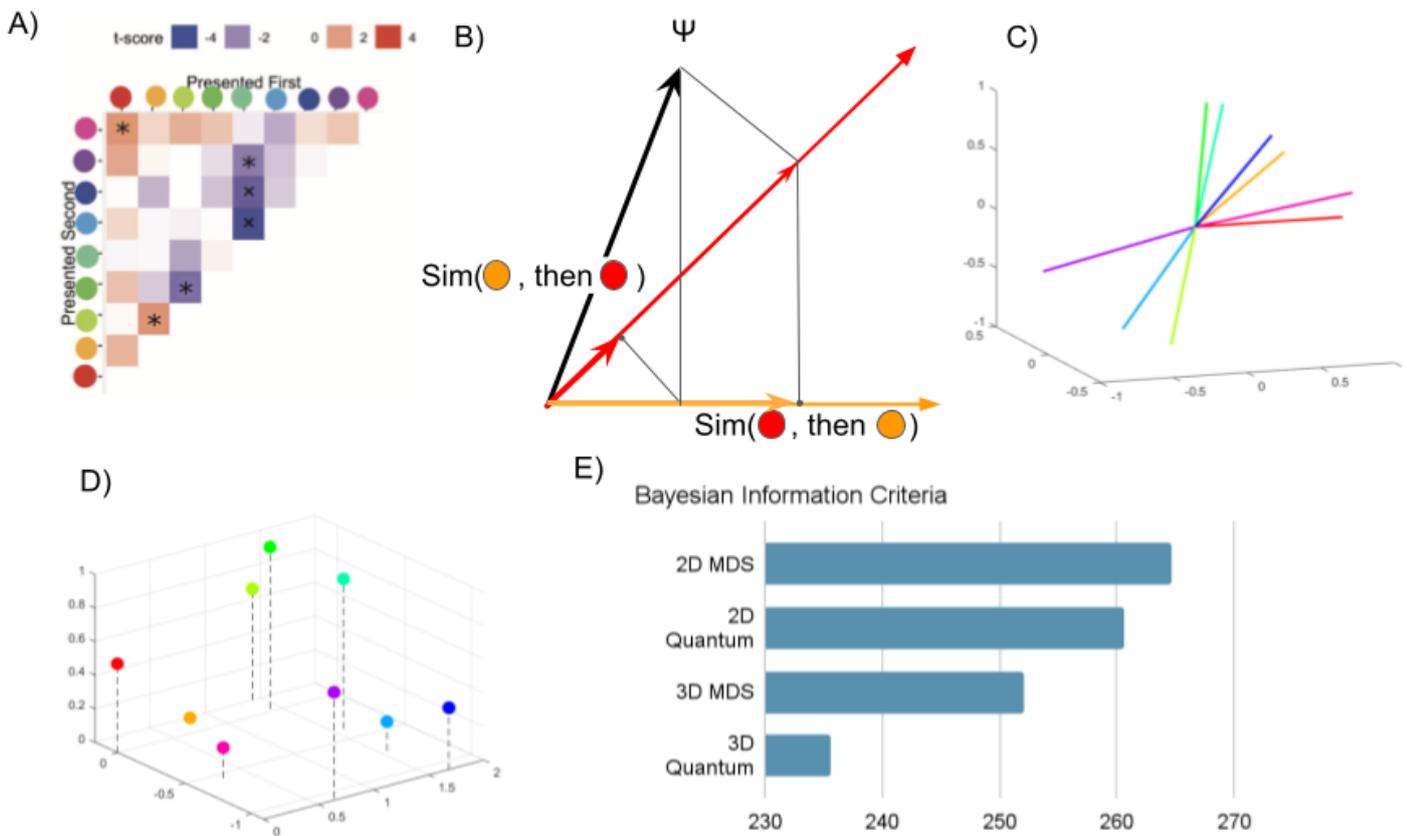
560 The extremely high citation rate of Tversky's paper attests to the fact that researchers are aware of  
561 this asymmetry. Yet, it is not common to empirically take asymmetries into account in similarity  
562 studies, as this doubles the numbers of trials. Even when different orders are included, researchers  
563 often remove them by symmetrising the originally asymmetric similarity matrix, so that they can use  
564 popular, existing analytic algorithms, such as multidimensional scaling.

565

566 While an isolated instance of asymmetry (e.g., "Is China similar to North Korea" vs. "Is North  
567 Korea similar to China", ([Tversky, 1977](#))) can be explained in many possible models, a collection of  
568 perceptual reports for many stimuli, such as color patches, and a particular pattern of asymmetries  
569 across many stimuli represent a more substantial challenge (Figure 3A). Epping et al.'s quantum  
570 models, which consider a state as a density matrix (this is a generalization of the idea that a state

571 can be a vector), and similarity as arising from sequential projections (Figure 3B), offered a better  
 572 fit to the empirical data (Figure 3C), compared to points-in-space models of qualia (Figure 3D, E),  
 573 with flexibility to accommodate asymmetry when mapping distance between points to similarity.  
 574

575 As noted previously, most similarity experiments tend to ignore the effect of order of presentation,  
 576 using a simultaneous presentation paradigm, or paradigms that allow longer and uncontrolled  
 577 inspection of the items. This is understandable due to the increased cost of experiments that  
 578 manipulate order, because the number of the trials increases quadratically with the number of  
 579 items to examine. Distributing pairs of items across many participants in online samples may solve  
 580 this issue ([Kawakita et al., 2023](#)).  
 581  
 582



583  
 584

585 **Figure 3. Quantum model of color similarity.**

586 A) Empirical asymmetry matrix. The raw similarity matrix is subtracted from its transpose to reveal  
 587 the degree of asymmetry in similarity judgements. Taken from ([Epping et al., 2023](#)). B) How  
 588 quantum operations (projections) give rise to perceived similarity ([Epping et al., 2023](#); [Pothos et](#)  
 589 [al., 2013](#); [Yearsley et al., 2022](#)). Assume an initial (mental) state as a unit vector  $\Psi$  (the black line).  
 590 Color qualia observables {red and orange} are represented as two “subspaces” in a space (the red  
 591 and orange axes). The vector is projected onto a subspace representing the color that is first  
 592 experienced. From there, it is further projected onto the subspace corresponding to the second  
 593 color. The resulting length of the final projection can be related to the perceived similarity between  
 594 the two colors. Importantly, the resulting length can depend on the order with which the colors are  
 595 experienced. C) The best fit quantum similarity model for the data in (A) ([Epping et al., 2023](#)). In  
 596 the quantum model, each of 9 color qualia observables is modeled as a subspace in 3D space.

597 Experienced similarity between the two subspaces is related to the square value of the cosine  
598 angle between them (e.g., the red and the pink subspaces have a narrow angle, but the red and  
599 the green subspaces have a near 90 deg angle). D) Traditional 3D MDS representation of 9 colors  
600 based on their pairwise similarity. E) Bayesian information criteria (BIC) for best fit 2D and 3D MDS  
601 and quantum models. Note that MDS models needed additional free parameters to account for  
602 asymmetries in similarity judgements ([Nosofsky, 1991](#)), resulting in more complex models. The 3D  
603 quantum model offered the best fit to the empirical data.  
604  
605

---

606  
607

608  
609

#### 610 **4.2 Violation of the Bell inequality in the domain of qualia.**

611

612 Quantum theory was developed in the 1920s by Bohr, Heisenberg, Shroedinger, Born and others.  
613 This theory challenged the predominant realist view of nature. In 1935, Einstein, Podolsky and  
614 Rosen ([Einstein et al., 1935](#)) (EPR) challenged this view, claiming that quantum theory is  
615 incomplete. In 1962, Bell discovered one fundamental inequality ([Bell, 1964](#)) must be satisfied  
616 assuming EPR's view is correct. Subsequently, the violation of the Bell inequality was empirically  
617 demonstrated ([Aspect et al., 1982; Freedman & Clauser, 1972](#)). The Nobel Prize for Physics in  
618 2022 was awarded for the demonstration of violations of the Bell inequality.  
619

620

621 Since the initial EPR experiments, there has been debate about loopholes in the experiments that  
622 were being conducted. Over the years these loopholes have been successively closed. Nowadays,  
623 it is generally accepted that the EPR experiments do empirically verify that microscopic particles  
624 can violate the Bell inequalities and are therefore entangled. What this implies about the underlying  
625 nature of these particles has been debated ([Zeilinger, 2010](#)). In parallel, a classical realist view has  
626 been questioned in relation to cognitive phenomena when these violate the Bell inequalities ([Bruza  
627 et al., 2023](#)).

628

628 Bell's inequality can be represented as follows:

$$629 S = E(a,b) - E(a,b') + E(a',b) + E(a',b'),$$

630 where  $a$  and  $a'$  are two measurement settings for system A,  $b$  and  $b'$  for B, and  $E(\cdot)$  is the expected  
631 value of the corresponding measurements. These expected values have to be measured in  
632 separate experimental conditions. In classical systems,  $|S| \leq 2$ , unless there are direct influences  
633 or signaling, between measurements of system A and system B. Contextuality-by-Default (CbD) is  
634 a generalization of the Bell inequalities. CbD allows a determination of contextuality in the  
635 presence of direct influences. (For its application, see ([Basieva et al., 2019; Cervantes &  
636 Dzhafarov, 2019](#))). The Bell inequality can be violated by quantum phenomena. A generally  
637 accepted explanation for the violation is that the properties of the phenomena do not have definite  
638 values at all times, that is, they are indeterminate.  
639

640

640 For the QQ hypothesis, demonstrating that qualia violate the Bell inequality will play a similarly  
641 fundamental role. If these types of inequalities are violated, qualia can be assumed to be quantum-  
642 like (which implies additional properties, such as noncommutativity). There are many ways to  
643 psychophysically test the Bell inequalities ([Basieva et al., 2019; Bruza et al., 2023; Cervantes &  
644 Dzhafarov, 2019](#)).

645

646 **4.2.1 Establishing violations of the temporal Bell inequality in multistable perception**

647

648 Multistable perception ([Brascamp et al., 2018](#); [Maier et al., 2012](#)) can be used to demonstrate  
649 violations of a type of Bell inequality. Atmanspacher and Filk ([Atmanspacher & Filk, 2010](#)) focused  
650 on the number of reversals between three time points of an ambiguous figure. They proposed  
651 empirical tests involving the temporal version of the Bell inequality ([Yearsley & Pothos, 2014](#)).  
652 Specifically, Atmanspacher & Filk's proposal was to measure perceptual switches between times  
653  $t_1$ ,  $t_2$ , and  $t_3$ , where  $t_1 < t_2 < t_3$ , selecting two time points per condition and for all three possible  
654 combinations. The probability of the perceptual state being different at time  $i$  vs time  $j$  is denoted by  
655  $p_{ij}$ . If qualia are determinate at all time (as hypothesized Figure 5 and Table 1 of Atmanspacher &  
656 Filk 2010), then it has to be the case that  $p_{12} + p_{23} \geq p_{13}$ . If violations of this inequality are found  
657 under some conditions, it gives reason to believe that the qualia are generally indeterminate, which  
658 is fundamental to the QQ hypothesis. (Note that qualia can be in a determinate state under some  
659 conditions under the QQ. Indeterminacy includes determinacy as a special case).

660

661 On the other hand, if qualia are generally determinate and can never be indeterminate,  $p_{12} + p_{23} \geq$   
662  $p_{13}$  have to always apply. Without doubt, there will be many instances of qualia which indeed  
663 behave in such a classical way (as we noted above, the classical probability theory is a special  
664 case of the quantum probability theory). What is of interest is whether we can identify cases of  
665 qualia for which  $p_{12} + p_{23} \geq p_{13}$  is violated. When this happens, then we can conclude that the  
666 qualia should be considered quantum-like in general (even if they might be classical-like, in many  
667 cases)<sup>12</sup>. The research effort for identifying such violations is still in its infancy, but there are  
668 already some promising results ([Waddup et al., 2023](#)) that showed violations of the temporal Bell  
669 inequality within a decision paradigm.

670

671 A closely related phenomenon concerns quantum Zeno effects ([Atmanspacher et al., 2004](#);  
672 [Yearsley & Pothos, 2016](#)). Quantum Zeno effects are the surprising prediction that, everything else  
673 being equal, an increased frequency of measurements can slow down change in the relevant state.  
674 Yearsley and Pothos (2016) demonstrated the Zeno effect at the cognitive level (i.e., the switch of  
675 opinion about someone to be judged from guilty to not guilty over the accumulated evidence. If  
676 "measurements" do not affect qualia, any kind of gradual changes in qualia should not be affected  
677 by measurements. While multistable percepts change spontaneously, other types of qualia  
678 changes, such as morph-induced categorical perception and gradual change blindness, can be  
679 used to test if the effects of measurement can be precisely predicted from the quantum formulation  
680 of the Zeno effects ([Atmanspacher et al., 2004](#); [Yearsley & Pothos, 2016](#)).

681

682 **4.2.2 Establishing violations of Bell inequality in multiple qualia about an object**

683

684 Another way to test the Bell inequality is to set up a task with at least three qualia observables,  
685 measuring two observables at a time, but against three different states. If qualia can be modeled  
686 classically and if measurements do not change qualia, then we expect the logical constraints, as  
687 exemplified by a Venn diagram (Figure 4A) to be satisfied by the set of probabilities. A simple

---

<sup>12</sup> It is worth repeating here that even if we were to find violations of temporal Bell inequality, it does not mean that brains that support qualia are operating in non-classical mechanisms. Instead, it would exclude mathematical structures for qualia that are purely based on classical notions (e.g., determinacy). Rather more broader mathematical structures, such as quantum-like, need to be considered.

688 diagrammatic analysis reveals various inequalities, described by George Boole as “conditions of  
689 possible experience” (Pitowsky, 1994). Pitowsky convincingly argues that quantum phenomena  
690 violate Boole’s “conditions of possible experience” as these are predicated on an assumption of  
691 realism. As quantum phenomena do not always have definite properties at all times, like marbles  
692 being pulled from an urn, they can violate probabilistic relationships expressed in these  
693 inequalities.

694  
695 Figure 4A demonstrates probability relationships amongst the three averaged measurement  
696 outcomes about three qualia observables, Color={red, purple, orange, ... }, Position={up, down,  
697 center, left, right}, and Shape={circle, octagon, hexagon,...}. Let’s say, you are briefly presented  
698 with an object and you experience it with associated (narrow-sense) qualia. In classical theory,  
699 these qualia should stay the same regardless of which of two observables you report. Let  
700  $\text{Prob}(C=\text{'red'})=p(R)$ ,  $\text{Prob}(S=\text{'circle'})=p(C)$ , and  $\text{Prob}(P=\text{'left'})=p(L)$  represent the probability that the  
701 averaged measurement outcomes of your qualia observables of the object is red, circular, and on  
702 the left, respectively. Then, we obtain that  $p(R)-p(R,C)-p(R,L)+p(C,L)$  has to be always non-  
703 negative. This is easily confirmed from a Venn diagram (Figure 4A).

704  
705 Now, imagine the object was “masked” to reduce its visibility or two such objects are  
706 simultaneously tested. The three properties can be randomly changed from trial to trial. In such a  
707 situation, your answers are likely to become probabilistic, that is  $\text{Prob}(C=\text{'red'})$ ,  $\text{Prob}(S=\text{'circle'})$ ,  
708  $\text{Prob}(P=\text{'left'})$  are all smaller than 1. But, answers will still have to satisfy various probabilistic  
709 constraints. For example,  $p(R)-p(R, C)-p(R, L)+p(C, L)$  has to be greater than or equal to 0, if these  
710 qualia properties follow the common sense assumptions regarding the objects being observed.  
711 Boole termed such probabilistic constraints “conditions of possible experience”. It is worth noting  
712 that classical intuitions regarding the averaged measurement outcomes are so entrenched, it is  
713 hard to imagine how things could be otherwise. Violations of such Venn diagram constraints can  
714 physically arise and are even easy to demonstrate in a classroom using just 3 polarizers (Figure  
715 4B and C, <https://www.youtube.com/watch?v=zcqZHYo7ONs>). This is an excellent demonstration  
716 to become familiar with the interesting reality of quantum phenomena, directly observable at the  
717 macro level.

718  
719 Bruza and colleagues (Bruza et al., 2023) examined this constraint for qualia of a face. They  
720 considered three qualia observables. Whether faces appear trustworthy={yes, no}, dominant={yes,  
721 no}, and intelligent={yes, no} (Figure 4D). It turned out that in this case, the Boole’s “possibility of  
722 experience” was violated (i.e.,  $p(A)-p(A,B)-p(B,C)+p(C,A)<0$ ), implying that the simple classic  
723 probabilistic picture in Figure 4A is inappropriate<sup>13</sup>.

724  
725 Several extensions to the above task are possible. For example, it is plausible that the degree of  
726 violation of the Bell inequality may depend on the characteristics of the qualia. If this were the  
727 case, performing the same face experiment but with reduced visibility might induce greater  
728 violations of the Bell inequality. Visual psychophysics offer a multitude of techniques to reduce  
729 visibility of an object (Kim & Blake, 2005; Stein & Peelen, 2021). As mentioned in the opening  
730 section, one of the fundamental visibility manipulations is masking. It is interesting to note that  
731 masking among three objects (Breitmeyer et al., 1981; Dember & Purcell, 1967) has been reported  
732 to be quite complex and might reveal a promising alternative demonstration of Bell inequality  
733 violations.

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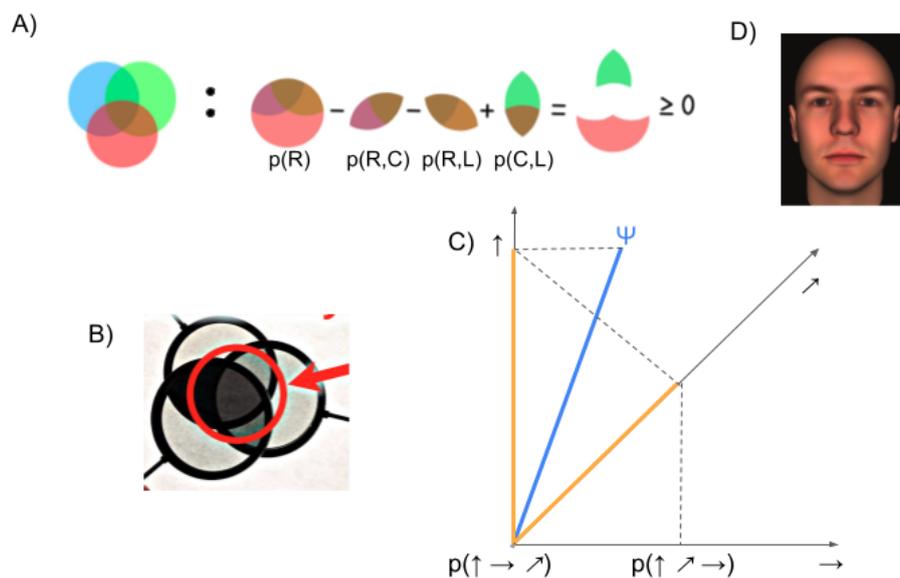
<sup>13</sup> Note that this does not mean that the quantum-like explanation is unique and the only way to explain this result. Rather, quantum theory is able to bring together a body of insights and mechanisms, in a coherent, axiomatic framework.

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One might argue that properties of faces, such as trustworthiness, dominance, and intelligence are not directly experienced qualia, but rather they are cognitively inferred constructs or concepts (Kemmerer, 2015; McClelland & Bayne, 2016). It would be a fruitful future experiment to examine if similar conclusions can be obtained when using more perceptual aspects of qualia of an object, such as color, orientation, size, location, and so on.

To sum up, one explanation for a violation of a Bell inequality is that the underlying phenomena do not have well-defined properties that exist prior to observation and are distributed in a certain manner (Pitowsky, 1994). Consequently, when the inequality is violated, there is reason to believe that the phenomena are indeterminate prior to measurement. While superficially simple, definitive tests of such inequalities are subject to several checks and assumptions (Blasiak et al., 2021), and this makes it hard to definitely establish the inference from violations to indeterminacy.

While the fundamental ideas are fairly simple, almost no research on qualia has adopted a task design, where three qualia observables are measured under three states. This is understandable given that it would be difficult to motivate such a task or interpret the results, in the absence of a quantum-like theoretical framework. We believe there is a huge opportunity to test novel ideas about consciousness with the QQ formulation involving three or more observables.



755

756 **Figure 4. Classical probability predictions and their violations in perceptual and quantum**  
757 **phenomena.**

758 A) Venn diagram of Boole's idea of possible experience. B) Intuitive physical demonstration of the  
759 violation of the Venn diagram constraints using polarizers. See  
760 <https://www.youtube.com/watch?v=zcqZHYo7ONs>. The main idea is this: prepare 3 polarizers. By  
761 arranging two of them, you can completely block any light through them. That is, the probability of  
762 passing photons across two polarizers can be set to 0. Then, insert a third polarizer between the  
763 two. Depending on the angle of the third, the three filters can pass more photons, and thus the  
764 output beam would be brighter at the intersection of the three polarizers. C) An explanation of (B)  
765 with a quantum projection scheme. Assume the state can be influenced by measurement. After we

766 project the initial state  $\Psi$  to the  $\uparrow$  axis, further projection to the  $\rightarrow$  gives 0 length, which corresponds  
767 to a perfect block of photons. However, if we project to the  $\nearrow$  axis, after the  $\uparrow$  one, then third  
768 projection to the  $\rightarrow$  gives a non-zero length, explaining why more photons pass through three filters  
769 than just the two original ones. D) A face used in ([Bruza et al., 2023](#)), where the relationship in A)  
770 does not hold for three aspects of the face (dominance, trustworthiness, and intelligence).  
771 Consequently, there is reason to believe that some of these facial traits were indeterminate prior to  
772 judgment.

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#### 775 **4.3 Dual-task interference and non-interference between qualia in terms of incompatible and** 776 **compatible observables.**

777

778 The relationship between consciousness and attention is one of the most debated topics in  
779 psychology, neuroscience and philosophy ([Block, 2007](#); [Bor & Seth, 2012](#); [Bronfman et al., 2019](#);  
780 [Cohen et al., 2012](#); [Dehaene et al., 2006](#); [Hardcastle, 1997](#); [Iwasaki, 1993](#); [Koch & Tsuchiya,](#)  
781 [2007](#); [Lamme, 2003](#); [Maier & Tsuchiya, 2021](#); [Mole, 2008](#); [Pitts et al., 2018](#); [Tallon-Baudry, 2011](#);  
782 [van Boxtel et al., 2010a](#)). QQ is quite consistent with the known empirical findings. Moreover, QQ  
783 makes further testable predictions which are critical to empirical research in this area.

784

785 Traditionally, sensory inputs are considered to be filtered by attention first (Figure 5A), implying  
786 that attention is necessary for consciousness. Information selected with attention is experienced as  
787 qualia and subsequently reported in a feedforward manner. Only some aspects of sensory input  
788 are attended, which ostensibly give rise to particular qualia. Behavioral reports reflect the  
789 experienced qualia. In this model, typically, attention is considered as a single limited resource and  
790 any task consumes some amount of attention.

791

792 This view goes against empirical findings concerning reports of sensory inputs outside of attention.  
793 Among many empirical findings, a particularly intriguing one is a pattern of the tasks that consume  
794 almost all attention and those that do not consume any attention, as shown in Figure 5B. These  
795 properties of task combinations have been documented over the years within the “dual task”  
796 research program ([Braun & Julesz, 1998](#); [Braun & Sagi, 1990](#); [Bronfman et al., 2019](#); [Fei-Fei et al.,](#)  
797 [2005](#); [Matthews et al., 2018](#); [Pastukhov et al., 2009](#); [Reddy et al., 2004](#)). For example, conscious  
798 experience of genders presented at the periphery do not differ with or without performing a difficult  
799 central letter task. Meanwhile, the experience of red/green bisected disks becomes totally unclear  
800 under a dual-task with the same central task ([Reddy et al., 2004, 2006](#)). Notably, this is even the  
801 case when the disk and the face are superposed transparently at the same location ([Matthews et](#)  
802 [al., 2018](#)). One possible explanation of this pattern is the existence of attention-free specialized  
803 modules in the cortex, possibly due to biological significance or extended training ([VanRullen et al.,](#)  
804 [2004](#)).

805

806 There are many alternatives to the traditional view of attention and consciousness. One view  
807 considers consciousness and attention to operate independently (Figure 5C) ([Koch & Tsuchiya,](#)  
808 [2007](#); [Lamme, 2004](#)). In this scheme, unattended conscious and attended unconscious processes  
809 are both possible. Attention and consciousness do not proceed in a feedforward manner. While  
810 this view is consistent with empirical findings, it does not explain how consciousness and attention  
811 interact dynamically.

812

813 The QQ hypothesis (Figure 2, Figure 5D) explicitly considers how qualia can be affected by  
814 attention through the formalism of instruments. This does not mean that all qualia are equally  
815 affected by attention, as demonstrated by the dual task. In fact, QQ provides two novel  
816 explanations about why a given pair of tasks may not interfere with one another.  
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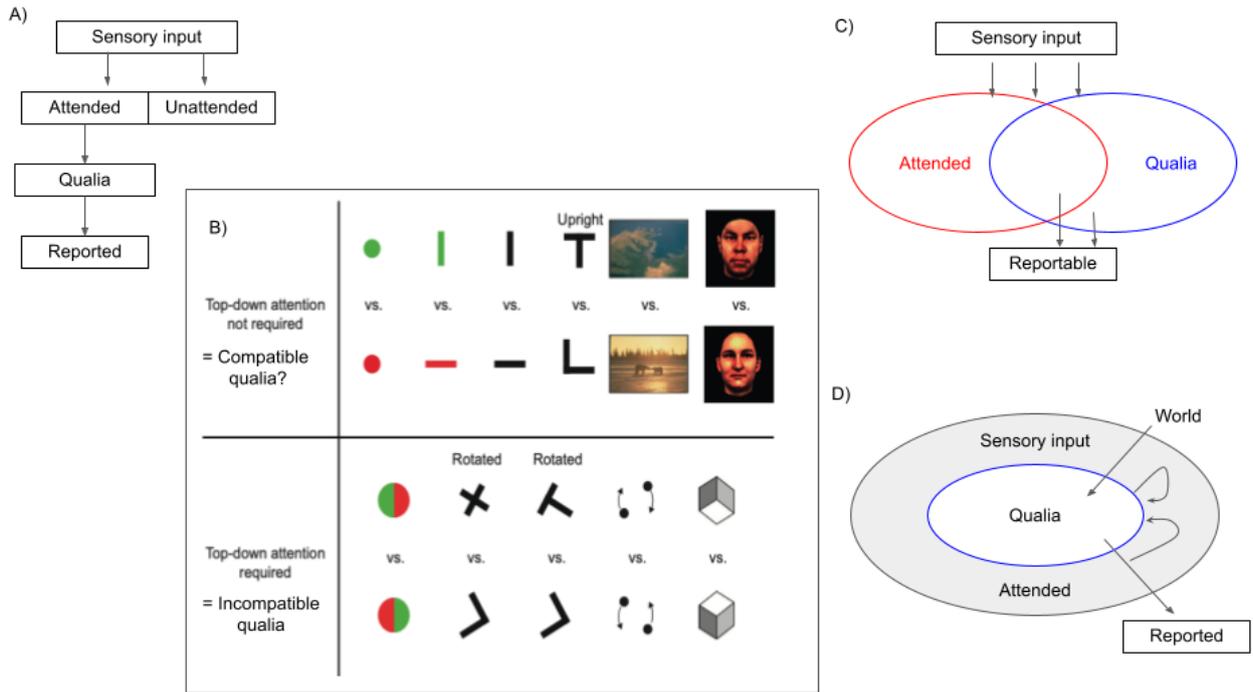
818 One explanation has to do with the existence of “commutative” qualia. While any process is  
819 generally noncommutative (See 3.6.1), in quantum theory, some observables, called “centers”, are  
820 always commutative with any other observables. Centers do not show any order effects. Such  
821 observables include mass. It is plausible that some types of qualia (e.g., extreme pain, bright light,  
822 loud sound) may also behave like centers and be commutative with other types of qualia. These  
823 would also be predicted to be less affected by states of measurement including attention. This is  
824 an empirical question for future research, which can be addressed by testing the presence of order  
825 effects in similarity experiments, for example.  
826

827 Another explanation relates to the idea of “incompatibility”. In quantum theory, when the properties  
828 of two or more observables cannot not be generally established together, these observables are  
829 called “incompatible”. According to QQ, pairs of qualia observables that cannot be simultaneously  
830 established are deemed “incompatible”.  
831

832 From the QQ perspective, it is important to point out that, in many dual tasks, a letter discrimination  
833 task is used as the primary difficult fixation task ([Matthews et al., 2018](#); [Tsuchiya & Koch, 2015](#)).  
834 Thus, the conclusions from these studies may be revealing “incompatibility” between qualia  
835 observables of letters and others. In other words, some qualia observables, such as face gender  
836 ([Matthews et al., 2018](#)) and the presence of animals in a natural scene ([Li et al., 2002](#)) (Figure 5B  
837 top row), may just be “compatible” with a letter qualia observable. These qualia observables may  
838 be “incompatible” with others. If the attentional interference happens only at the task level, we  
839 should not expect systematic patterns in interference *and* order effects. However, if interference is  
840 a result of the incompatibility between specific qualia combinations, then interference would result  
841 in specific order effects with a quantitative explanation based on a quantum-like model ([Epping et  
842 al., 2023](#)).  
843

844 Reconsidering the patterns of attentional limits in terms of incompatibilities between observables  
845 might allow novel insights into the qualia-attention research. With traditional psychological theories,  
846 we consider attention as a fixed resource ([Joseph et al., 1997](#)), which can amplify aspects of  
847 qualia, it is hard to explain why in some visual illusions stronger attention leads to poorer visibility  
848 of the target ([Schölvinck & Rees, 2009](#); [van Boxtel et al., 2010b](#)). Further, it is also hard to  
849 understand why distracting participants sometimes leads to better psychological performance in  
850 various paradigms ([Koch & Tsuchiya, 2007](#); [Tsuchiya & Koch, 2015](#)). Attention can change the  
851 neuronal circuitry momentarily ([Gilbert & Li, 2013](#); [Harris & Thiele, 2011](#)), thus it might be possible  
852 to understand such effects as a change, for a pair of observables, from incompatible into  
853 compatible. This change can be formalized as an instrument where attention as a state affects  
854 qualia observables. This explanation offers a coherent explanation of these seemingly odd  
855 relationships between qualia and attention.  
856

857 Unlike the limited resource model, QQ predicts an existence of pairs of “compatible” qualia  
858 observables, even though each one consumes a significant amount of a presumed attentional  
859 “resource”. QQ also predicts pairs of “incompatible” qualia observables, which cannot be  
860 simultaneously established, even if each does not consume much attentional resource.  
861 Discoveries of such pairs of qualia observables would further support QQ.  
862



864

865 **Figure 5. QQ is compatible with the empirical findings about the relationship between attention and**  
 866 **qualia.**

867 A) Traditional feedforward models of sensory input, attention, qualia, and reports (taken from  
 868 [Lamme, 2004](#)). B) Top row: a list of peripheral perceptual discriminations that can be conducted  
 869 simultaneously with difficult letter discrimination tasks at the fixation. For example, conscious  
 870 experience of genders presented at the periphery does not differ with or without performing a  
 871 difficult central letter task ([Matthews et al., 2018](#)). Bottom row: a list of tasks that cannot be  
 872 performed concurrently with the letter task. One novel interpretation of such results is using the  
 873 notion of incompatibility. Incompatibility is the inability to jointly establish the values of two or more  
 874 observables. Modified from ([Tsuchiya & Koch, 2015](#)). C) A static view of consciousness and  
 875 attention that is consistent with dissociations between qualia and attention ([Maier & Tsuchiya,](#)  
 876 [2021](#)). D) Quantum qualia hypothesis (reproduced from Figure 2).

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881 **5. Conclusion**

882

883 We proposed a Quantum-like Qualia (QQ) hypothesis based on a quantum theoretical framework  
 884 (e.g., noncommutative observables, states, and instruments; Figure 2, Table 1). QQ proposes  
 885 qualia as observables, not the “things” or results of “cognitive processes” as traditionally assumed.  
 886 QQ explains intuitive and known properties of qualia, such as their inherent indeterminacy,  
 887 dynamics, and interaction with attention. Predictions from QQ can be empirically tested with  
 888 demonstrations of asymmetry in perceptual similarity judgements, violations of the Bell inequality,  
 889 and apparent incompatibilities between particular qualia. Amongst these, particularly powerful are  
 890 demonstrations of Bell inequality violations. In order to test them, we minimally need to measure  
 891 three observables, two at a time across three different states (Figure 4). Such experiments have  
 892 been rarely conducted systematically, due to the lack of theoretical background and motivation.

893 Additionally, there are subtle loopholes that need to be considered, before compelling empirical  
894 evidence is provided that substantiates our claim that qualia are indeterminate ([Atmanspacher &](#)  
895 [Filk, 2019](#); [Basieva et al., 2019](#); [Emery, 2017](#)). In physics, it took more than twenty years from the  
896 theoretical proposal by Bell through to the initial experiment by Clauser and then to the compelling  
897 demonstration by Aspect (Section 4.2.1). Will a similar pathway await the Quantum-like Qualia  
898 hypothesis in the future? Only time will tell. With increasing evidence that QQ provides a coherent  
899 explanation on the mathematical structure of qualia, QQ may well emerge as a promising  
900 mathematical and philosophical framework to link qualia and the brain.

901  
902

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