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Insights from quantum cognitive models for organizational decision making

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ABSTRACT

Organizational decision making is often explored with theories from the heuristics and biases research program, which have demonstrated great value as descriptions of how people in organizations make decisions. Nevertheless, rational analysis and classical probability theory are still seen by many as the best accounts of how decisions *should* be made and classical probability theory is the preferred framework for cognitive modeling for many researchers. The focus of this work is quantum probability theory, an alternative probabilistic framework. Results in decision making, which appear paradoxical from a perspective of classical probability theory, may make perfect sense if one adopts quantum probability theory. We review some cognitive models of decision making based on quantum probability theory. Each of these models is based on a challenge to prescription from classical probability theory. The transition from labeling a particular behavior as irrational, by classical probability standards, to (potentially) rational (or, at any rate, not fallacious), raises interesting possibilities, including that of characterizing certain heuristics in formal, probabilistic terms.

1. Introduction

In psychology, the classical rational model of decision making assumes that decision makers comprehensively define a problem, understand all possible alternatives and their consequences, and select the very best action after evaluating all the available options (e.g., Anderson, 1991; March, 1997; Simon, 1979). Moreover, all probabilistic computations are assumed to be carried out in a way which conforms to the prescription from classical probability (CP) theory. The link between rationality and CP theory can be justified in important a priori ways, such as the Dutch Book argument (e.g., Howson & Urbach, 1993), which shows that CP reasoning is consistent/coherent, in a certain formal sense (Oaksford & Chater, 2009; Tenenbaum, Kemp, Griffiths, & Goodman, 2011).

Yet many researchers have questioned the relevance of the classical rational model and CP theory in modeling human decision making, especially in the case of applied decision making situations (see also, e.g., Wakker, 2010, for arguments relating to risk and loss aversion). The focus of the present article is organizational decision making. In such cases, decision makers are often assumed to have limited cognitive resources and are faced with environments which are uncertain, complex, and go beyond the assumptions and manipulations of laboratory-based decision tasks. As a result, it has been argued that decision makers operate within the limits of 'bounded rationality', frequently 'satisficing' by making good enough decisions (Simon, 1955) and adapting to their environment by using heuristics and intuition, which can both enhance (e.g., Gigerenzer & Todd, 1999; Gigerenzer, 1991; Klein, 1998) and bias decision making (e.g., Kahneman & Tversky, 1996; Kahneman, Slovic, & Tversky, 1982). Moreover, working in complicated, often emotionally charged, organizational systems, decision makers have to respond to the needs of multiple stakeholders, who can politically influence the decision making process (e.g., Cyert & March, 1963; March & Simon, 1958; Pfeffer, 1981) and both influence and are influenced by the context and the situated, embodied aspects of cognition, in which the decision is being made (e.g., Niedenthal, Barsalou, Winkielman, Karuth-Gruber, & Ric, 2005; Weick, 1995; Wheeler, 2005).

All these are considerations which undermine the descriptive adequacy of CP theory decision making models and the rational analysis approach, in situations of applied decision making. Be that as it may, for many researchers, rational analysis still provides the

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prescription for how decision makers *should* reason, on the basis of the available information. We think this normative aspect of prescription from CP models in a given situation is particularly significant, especially in the case of applied decision making, where, clearly, there is an extra onus to ensure that decisions are as 'correct' as possible. Relatedly, because of this point, it is the case that many researchers still find appealing cognitive modeling on the basis of CP principles (e.g., Oaksford & Chater, 2009), despite the evidence that, in many practical situations, modeling approaches based on e.g., heuristics and biases may have a higher descriptive value (Gigerenzer & Todd, 1999; Gigerenzer, 1991; Kahneman & Tversky, 1996; Kahneman et al., 1982).

It is these points which motivate the approach in the present article, based on quantum probability (QP) theory. QP theory is a formal framework for how to assign probabilities to events, and so it is possible to develop some normative arguments for QP theory, analogous to those for CP theory (Pothos & Busemeyer, 2014). Equally, some processes in QP theory appear to have natural interpretations in terms of existing, well-known heuristics, such as the representativeness or availability heuristics (cf. Busemeyer & Bruza, 2012; Pothos & Busemeyer, 2013). It is then possible that QP theory can provide a perspective on organizational decision making, which is close to descriptive assumptions from relevant heuristics and biases and, equally, consistent with the general, a priori arguments, which motivate CP accounts and corresponding normative considerations. Our specific objective is to provide some preliminary discussion of whether such an exciting (though, also, ambitious) objective might be achievable or not.

Many of the decision making phenomena that have been studied as part of the QP research program concern situations for which the normative (from CP theory) prescription goes against a very strong intuition for an alternative decision. Intuition has been defined as "affectively-charged judgments that arise through rapid, non-conscious, and holistic associations" (Dane & Pratt, 2007: 40). Intuition is seen as important in the use of heuristics (e.g., Kahneman & Tversky, 1982; Klein, 1998, 2003), produces decisions that can at times appear irrational, at least without detailed analysis (e.g., Klein, 1998), and as a process is itself difficult to explain rationally (Dane & Pratt, 2007). Both CP theory and QP theory are, in part, intended as theories for how intuitions regarding the relative likelihood of different possibilities develop. While the work just cited indicates a divergence between predictions from CP models and current understanding about intuition, a consideration of QP theory can lead to alternative conclusions.

QP theory was devised to explain paradoxical findings in quantum physics that could not be understood using classical theories. It is based on axioms fundamentally different from those of CP theory and so corresponding probabilistic inference involves characteristics (such as superposition, incompatibility, and entanglement), with no analogs in classical theory. It has helped physicists understand, for example, how different events within a system interfere with one another and how the measurement of a system influences the state of the system. Such phenomena are also observed in decision making research, for example, in relation to order effects (e.g., Hogarth & Einhorn, 1992) and the constructive role that making a choice can have on underlying preferences (e.g., Payne, Bettman, & Johnson, 1993; Sharot, Velasquez, & Dolan, 2010). So, proponents of the application of QP theory in cognition have argued that these special characteristics of QP align well with human decision making under uncertainty, at least under some circumstances. In fact, human decision making behavior, which may appear paradoxical or irrational from a classical perspective, often has a simple and natural explanation in terms of QP principles. Of relevance is also the fact that, in QP theory, the incompatibility of certain possibilities means that their probabilistic computation needs to be sequential, so that, for example, even conjunctions need to be assessed in a sequential way. Such requirements make QP theory computation closer to process assumptions and so, perhaps, more suitable for modeling the situations of applied decision making that we are interested in. In general, it has been suggested that incorporating process assumptions into cognitive models is an appropriate direction for their development (Jones & Love, 2011; cf. Newell, 1990).

The structure of our contribution in this Special Issue is as follows: first, we will briefly summarize QP theory and consider the motivation for exploring its application in cognitive modeling. It is not our intention to provide a comprehensive overview of QP theory research, for reviews see, for example, Busemeyer and Bruza (2012), Khrennikov (2010), Pothos and Busemeyer (2013) and Wang, Busemeyer, Atmanspacher, and Pothos (2013). Second, we will consider some of the key insights about human decision making, from existing QP cognitive models, as developed in the context of particular empirical applications (mostly based on Busemeyer & Bruza, 2012; Pothos & Busemeyer, 2009; Trueblood & Busemeyer, 2011; Wang & Busemeyer, 2013). The selection of empirical applications will be motivated from corresponding conclusions that human behavior deviates from the prescription of CP theory. Of course, there are often typically powerful non-CP theory accounts for such findings (e.g., Gigerenzer & Selten, 2001; Marewski & Schooler, 2011; Tversky & Kahneman, 1983). The emphasis on CP theory relates to the emphasis on normative considerations in this paper. As discussed, we think that this is a valuable approach, especially in situations of applied significance, where decision makers may be particularly keen to achieve decisions considered 'correct' in some formal sense (since deviations from normative prescription may lead to e.g., material loss). For each of these insights/applications, we discuss the new perspective that QP provides on organizational decision making and the possible implications and benefits. That is, our discussion will be more focused on the normative perspective (conflicts with CP theory and corresponding QP theory insights), less so by the descriptive or bounded rationality perspective, provided by models based on heuristics and biases (though, obviously, both perspectives are valuable).

Inevitably, some of the recommendations in this paper, in relation to QP theory, will involve speculation. Our work so far has focused on establishing the formal validity of QP cognitive models, against empirical results of high prominence in the decision making literature. There has been little systematic investigation or empirical research into the applicability of QP models in organizational settings (for exceptions see the work of Lawless and his colleagues discussing how principles of QP can be applied to modeling social dynamics, such as cooperation and competition, in teams and organizations; Lawless & Sofge, 2012; Lawless & Grayson, 2003; Lawless, Bergman, Louçã, Kriegel, & Feltovich, 2007; Lawless et al., 2011; see also Yukalov & Sornette, 2012, who apply their quantum decision theory (Yukalov & Sornette, 2008), a theory developed for individual personal decision making, to decision makers under the influence of other social agents). We hope that this paper can serve to inspire further work toward an applied direction for the QP cognition program, in relation to organizational decision making. The ideas we outline below provide an alternative perspective for rationality and optimality in probabilistic inference and motivate a discussion of implications (and possible aids) in organizational decision making.

2. An outline of quantum probability theory

QP theory is a theory for how to assign probabilities to events. It is best known in its application to physics, in the context of quantum mechanics. But, the rules regarding probabilistic assignment in quantum mechanics (what we call QP theory) have no essential physical content and can, in principle, be applied in any situation, where there is a need to formalize uncertainty. Well known applications of quantum theory outside physics are in information theory (e.g., Nielsen & Chuang, 2010) and information retrieval (e.g., Van Rijsbergen, 2004; Widdows, 2004).

The application of QP theory in psychology has been gaining momentum in recent years and spans a range of cognitive research themes, such as conceptual combination (e.g., Aerts, 2009; Aerts & Gabora, 2005), similarity (Pothos, Busemeyer, & Trueblood, 2013), memory (e.g., Bruza, Kitto, Nelson, & McEvoy, 2009), and perception (Atmanspacher & Filk, 2010). In decision making theory, note that, within the QP theory community, a number of different modeling approaches have been adopted (e.g., Aerts & Aerts, 1995; Basieva & Khrennikov, 2014; Bordley & Kadane, 1999; Bordley, 1998; Busemeyer, Pothos, Franco, & Trueblood, 2011; Khrennikov & Haven, 2009; Lambert-Mogiliansky, Zamir, & Zwirn, 2009; Pothos & Busemeyer, 2009; Trueblood & Busemeyer, 2011; Wang & Busemeyer, 2013; Yukalov & Sornette, 2008, 2009). We do not review these approaches in detail (for overviews organized in single volumes see Busemeyer & Bruza, 2012; Khrennikov, 2010, and the special issue of Topics in Cognitive Science, Wang et al., 2013). Instead, we focus on examples of models which we think provide simple illustrations of the main principles underlying QP cognitive accounts of decision making generally and the implications these have for organizational decision making.

The use of QP theory in psychology has enabled the introduction of several novel theoretical concepts. One new concept is that, in QP theory, certain questions are considered incompatible, meaning that certainty for one requires (ontic) uncertainty for the other. The idea of incompatibility is related to the existence of uncertainty relations; that is, the requirement that the combined uncertainty for particular pairs of questions can never be reduced below a minimum level. Another new concept is that a person's knowledge can be characterized as a superposition state, with respect to particular questions, which means that precise values for the corresponding questions do not exist, until a measurement is made. Finally, in QP theory cognitive states can be entangled, so that corresponding measurements may result in super-correlations, not possible in CP theory.

A lot of the strangeness of QP theory arises because events are represented as subspaces in a multidimensional vector space, called a Hilbert space.[1] By contrast, events in CP theory are subsets of a sample space. Greatly oversimplifying, the difference between QP and CP theory is one between a geometric representation of probabilities vs. a set-theoretic representation one. The implication of this difference is that the structure of events in CP theory is that of a Boolean algebra, but in QP theory it is only a partial Boolean algebra, meaning that, in the latter, operations like conjunction or disjunction are not defined for all possible pairs of possibilities (Hughes, 1989).

We aim to present our examples below, as much as possible, with little mathematical detail. So, we here discuss only the very basic aspects of how probabilities are assigned to events in QP theory (e.g., Isham, 1989). Consider the mental state of a participant, e.g., when contemplating which of two options to choose. This mental state is represented as a vector in a Hilbert space. Then, different events or choices for the relevant situation are represented as subspaces in the Hilbert space. Such subspaces can have any dimensionality. A fundamental assumption in QP theory is that the probability that the state is consistent with a particular event is the squared length of the projection onto the corresponding subspace.

[1] Hilbert spaces are vector spaces defined on a complex field endowed with an inner product, and having certain convergence properties as well.

Note, this means that mutually exclusive events have to be at right angles with each other. Incompatible events are represented as subspaces at oblique angles, relative to each other, such that the smaller the angle, the higher the classical correlation between these possibilities. Finally, if a person observes that an event is true, then a new cognitive state is formed by projecting the current state onto the subspace of the observed event. This is the "infamous" state reduction or "collapse" that occurs in quantum theory. We do not wish to discuss the mathematics of QP theory any further at this point, but rather flesh out some of the underlying principles, as this becomes relevant in the examples below.

3. Strategic decision making and incompatibility

Strategic decisions are characterized as being novel, ambiguous, complex, open-ended (Mintzberg, Raisinghani, & Theoret, 1976), and influenced by a diverse range of interacting social, emotional and political factors (e.g., Cyert & March, 1963; Eisenhardt & Zbaracki, 1992; March & Simon, 1958;Pfeffer, 1981; Tetlock, 1985). For example, if a decision maker is required to look at which new production technology they should invest in, he or she will need to consider objective information about the competing systems, alongside the different views held by stakeholders about the cost of the investment, the quality of the new technology and the time it will take to get production up and running. These various considerations represent distinct rationales which, depending on the power and social influence of the stakeholders, can diverge or overlap (e.g., Janis, 1972; Langley, 1995). This type of loosely structured context is said to foster the use of intuition in decision making (e.g., Klein, 1998; Shapiro & Spence, 1997). During the course of the decision making process, the various inputs may interact with one another, so that, for example, if the decision maker is certain that quality is an important factor, then perhaps their feelings about the importance of cost or time to production become less certain.

From a cognitive modeling point of view, the idea that the interaction of different cognitive events (e.g., a thought or a feeling) might influence a decision maker's intuition and final judgment is quite plausible and can be illustrated by the conjunction fallacy, one of the most famous phenomena studied in the heuristics-and-biases program. Tversky and Kahneman (1983) presented to participants a short vignette about a hypothetical person, Linda, who was described very much as a feminist, but not a bank teller. Then, participants were asked to rank order a set of statements about Linda. The critical statements were (1) that Linda is a bank teller (BT) and (2) that Linda is a bank teller and a feminist (BT & F). Participants ranked the latter as more probable than the former, hence indicating that they considered Prob(BT&F) > Prob(BT), a result that is called the conjunction fallacy. Since Tversky and Kahneman's (1983) seminal study, the conjunction fallacy has been frequently replicated with many other kinds of stimuli and experimental situations (though see e.g., Hertwig & Gigerenzer, 1999).

Tversky and Kahneman (1983) argued that the conjunction fallacy arises because Linda is very similar to the typical feminist, so that she is likely to be considered a probable bank teller and a feminist. It was suggested that this representativeness heuristic is what guides decision making and that, indeed, CP theory has nothing to do with cognition (at least in such cases). The conjunction fallacy is very hard to reconcile with a CP prescription, because CP theory is based on set theory and a single sample space for all events; a more specific event can never be more probable than an inclusive, more general one. Put differently, the hypothetical Lindas who are both F and BT can never be more numerous than the ones who are just BT. There have been, of course, explanations of the conjunction fallacy based on, e.g., heuristics (including Tversky & Kahneman's, 1983, one). However, as discussed, our emphasis here is the perspective from formal probability theory. If CP theory is considered a normative standard, and decision makers commit the conjunction fallacy, does that mean that it is incorrect to use a heuristic in this situation and instead is it more desirable to pursue correctives? The application of QP theory in the problem can help inform this key question.

The relationship between variables in decision making and the sequence in which they are considered, lies at the heart of *incompatibility*, one of the key concepts of QP. Bohr (1928), an early pioneer of quantum theory, introduced the concept. Interestingly, there is some evidence that Bohr may have been influenced by the work of James (1890a,b), who had considered these issues from a psychological perspective (Holton, 1970). In quantum theory, two observables or measurements which are non-commuting (e.g., position and momentum) are said to be incompatible. When measurements are incompatible they are subject to order effects so that measuring in one order may produce results different to measuring in a different order, AB ≠ BA. This is different from classical observables, which have to obey the law of commutativity in conjunctions (e.g., AB = BA). As observables in quantum theory are both properties of and operations on the state of the system, they can also be considered actions (Wang et al., 2013). This means that the effect of a given action sequence on an initial state will depend on the order in which those actions occur.

Busemeyer et al. (2011) have shown how a QP model can provide a natural account for the conjunction fallacy. The key assumption was that the possibilities that Linda is an F and, separately, a BT, are incompatible, so that they cannot be assessed concurrently. Therefore, the conjunction BT&F does not exist and, instead, one needs to evaluate the sequential conjunction BT& then F or F & then BT (Busemeyer et al., 2011, argued that the latter is more cognitively plausible). How does the QP model work? For incompatible questions, establishing the answer for one changes the perception for answering the other. In QP theory, probabilistic assessment can be strongly order and context dependent. Thus, for example, from the perspective of the initial story about Linda, she is extremely unlikely to be a BT. But, once participants have accepted the F property for Linda, then it is easier to recognize that feminists can have all sorts of professions. From this feminist perspective, it is easier to accept the possibility that Linda might be a BT (in both cases, 'easier' is relative to how easy it is to accept the possibility that Linda might be a BT, from the baseline perspective of just the story).

Translating this example into an applied context, strategic decisions that concern significant organizational change might illustrate how 'committing' the conjunction fallacy can make sense. In such situations, decision makers can be emotionally attached to existing strategies (e.g., Finkelstein, Whitehead & Campbell, 2008) and it is argued that, in order to change, decision makers need to loosen their emotional commitment (Eisenhardt & Martin, 2000; Hodgkinson & Healey, 2011; Teece, Pisano, & Shuen, 1997). Resistance to change can be a product of the perceived threat that the changes pose to social identities (e.g., Gioia, Schultz, & Corley, 2000; Haslam, Eggins, & Reynolds, 2003; Hogg & Terry, 2000). The ability of an organization to manage how its employees affectively react to organizational changes that impact on their social identity (e.g., Hodgkinson & Healey, 2011) and respond to the collective emotions of the organization (e.g., Huy, 1999, 2002) can be critical in the success of change initiatives. Having people make decisions that run contrary to their existing perceptions of their organization is difficult; large changes in identity are perceived as unattainable and small changes are perceived as irrelevant (Reger, Gustafon, Demarie, & Mullane 1994). One way through this is by exploiting the principles of QP, as demonstrated in the explanation of the conjunction fallacy, that the conjunction of two events can *increase* the probability of making a decision in a given direction, because accepting a more probable event can facilitate the acceptance of a less probable one (assuming the two events are linked, in some way).

Consider a new CEO of a manufacturing company. Strategically, she thinks that she needs to change the positioning of the company, to being more technologically advanced. Doing so will both increase the efficiency of production and also convey the right image of the organization to customers and shareholders that is needed to succeed in the future. The board needs to decide in favor of this change in strategic direction, but, historically, investment in new technology has not been a priority for this company and so the probability of them deciding to pursue it is low. Are there any conditions under which the board might decide to support the CEO's favored strategy?

Consider next an alternative approach the CEO could adopt. She suggests that strategically the organization needs to re-position itself as a more environmentally friendly firm, at the forefront of ensuring high environmental standards, which are increasingly favored by customers and subject to government guidelines and regulations. This argument might be easier to make, as it resonates with the importance of maintaining a revenue stream. Having made this argument and convinced the board, it might then become easier to persuade them to invest in new technology to improve efficiency, thereby making their production processes more environmentally friendly. Depending on the information presented and, critically, the sequence in which it is presented, the probability of the board selecting the CEO's preferred approach may be increased, in a way analogous to how the conjunction fallacy emerges. In other words, this is a case whereby the probability of a single change (being technologically advanced) is lower than the probability of a (quantum) conjunction (being environmentally friendly and then being technologically advanced; note, the quantum model predictions regarding the emergence of the conjunction fallacy are order-dependent, in relation to the consideration of the premises; Busemeyer et al., 2011). Having accepted the change in relation to being environmentally friendly, it becomes more plausible to accept the further change of being technologically advanced – the first change has a facilitatory effect on the second one, because the two share a causal connection. For this to be the case, the two changes have to be 'incompatible' (in the quantum sense) and, moreover, one change (which we can call the facilitatory change) has to make the target change one more plausible. Finally, clearly, facilitation can occur only if the changes are carried out in a certain order, from facilitatory to target.

This example from organizational decision making demonstrates how an explanation in formal terms can be provided by QP theory for a decision which, so far, could only be explained in heuristic terms. Of course, there are alternative explanations, for why, in the above example, the probability of the board accepting the proposal is influenced by the conjunction of those two particular options. For example, resistance may be diminished by linking one aspect of the change that does accord with peoples' social identity (being environmental friendly) with another aspect that does not (being technologically advanced). This and other perspectives can help elaborate the relevant cognitive processes. But, the conjunction fallacy has been labeled a fallacy because it does not make sense in terms of a normative perspective on decision making, based on CP theory. But, it is fully consistent with QP theory, an alternative formal probabilistic framework, which raises the question of whether the conjunction fallacy should really be considered a fallacy at all. The application of QP theory so helps elucidate the key question of normative guidance that we are interested in and it also demonstrates how the novel theoretical concepts in QP theory (in this case incompatibility) can help increase our understanding of human decision making.

4. Uncertainty, organizational change and violations of the law of total probability

Organizational inertia, the tendency of businesses, especially those at the maturity phase of the lifecycle, to continue operating in the same way, is an issue facing many organizations as they make decisions about strategy. Inertia typically precedes decline for many businesses, especially incumbent businesses facing the entry of new players in their markets, unless attempts are made to overcome their rigidity (Christensen & Rosenbloom, 1995; Tushman & Anderson, 1986). Such businesses demonstrate an apathy and reluctance toward change, preferring to stick with their established approaches (Miller & Friesen, 1980; Tushman & Romanelli, 1985) and defending previous decisions, in spite of evidence that demonstrates their failure (Staw, 1976; Staw & Ross, 1987). The difficulty of organizational change in this situation is often due to the strength of emotional attachment to previous strategies and the threat that the changes pose to self-esteem (e.g., Eisenhardt & Martin, 2000; Finkelstein et al., 2008; Hodgkinson & Healey, 2011; Teece et al., 1997; Tushman & Anderson, 1986). As Lewin (1951) argued, if people are happy with the status quo, regardless of what internal or external triggers for organizational change exist, there is no impetus for them to change.

From the perspective of modeling cognitive processes in decision making, this situation reflects what we will call the 'total probability trap'. The law of total probability is a fundamental principle in the mathematical structure of CP theory and is illustrated by the *sure-thing principle* described by Savage (1954). Savage demonstrated his principle using as an example, a familiar scenario in organizational decision making, a deliberation regarding a strategic investment. A business executive is contemplating investing in a property and he believes the outcome of the next American presidential election to be critical to the decision. After asking whether he would invest if a Democrat or Republican won the election and concluding that he would invest regardless of who won, the executive concludes that he should invest, even though he is uncertain about the outcome of the election. Note, according to the sure thing principle, $Prob(invest) = Prob(invest|republicn) \cdot Prob(republican) + Prob(invest|democrate) \cdot Prob(democrate)$, so that $Prob(invest)$ is bound by $Prob(invest|republican)$ and $Prob(invest|democrate)$. So, if the agent thinks he should be behaving rationally (a reasonable assumption!), then he may feel compelled to invest in the unknown case, in a way consistent with the law of total probability. This requirement clearly constrains possible behavior, but, as the following example shows, people's decision making is not always constrained by the law of total probability.

Shafir and Tversky (1992) provided an ingenious test of whether human decision making is consistent with the law of total probability. They had participants play a prisoner's dilemma game. As is standard in such games, there were two possible actions, defect (D) and cooperate (C) and two players, which, in Shafir and Tversky's experiment were the participant in the experiment and a hypothetical opponent. The combination of the action of the participant and the hypothetical opponent determined the payoff to both. The payoffs were set up in such a way, that no matter what the hypothetical opponent did, it was advantageous for the participant to D. Shafir and Tversky's (1992) experiment involved some so-called bonus trials, in which the participant was told of the opponent's action. Predictably enough, when a typical participant was told that the opponent chose to D, she would D as well; likewise, when she was told the opponent chose to C, by far the most common action was to D. The surprising finding was that, when the opponent's action was unknown, many participants reversed their action and chose to C. Thus, Shafir and Tversky (1992) showed that $Prob(D, unknown) \neq Prob(D \wedge known\ D) + Prob(D \wedge known\ C)$, so violating the law of total probability. Since this pioneering study, several other analogous results have been reported (e.g., Busemeyer, Wang, & Mogiliansky-Lambert, 2009; Croson, 1999).

The intuition about the psychological process in Shafir and Tversky's (1992) experiment is that there are perhaps good reasons for defecting under each of the 'known' conditions. For example, when a participant knows the opponent cooperates, it makes sense to choose to D, so as to make more money. When a participant knows the opponent defects, a D action makes sense, as retribution. But, these two reasons to D fail to come to mind in the unknown condition. It is as if, when there is uncertainty, these individually good reasons to D interfere with each other, that is, cancel each other out.

Regarding Shafir and Tversky's (1992) experimental situation, the classical prescription is straightforward. If you do action A, given X and you do action A, given ∼X, then you should do action A, regardless of whether you know about X or not. Pothos and Busemeyer (2009) showed how a quantum model for Shafir and Tversky's (1992) experimental situation reproduces the observed violations of the law of total probability (related applications are in Trueblood & Busemeyer, 2011; Wang & Busemeyer, 2013). What this means is that, although according to CP theory it is wrong to violate the law of total probability, according to QP theory, given that a person chooses action A, given X and, separately, given ∼X, then it can be correct (in the sense of probabilistic prescription from QP theory) to reverse his/her decision and do ∼A, in a situation where there is uncertainty about X. Note, it is not the case that a person *should* reverse action in the situation of unknown information, rather that, according to QP theory (and contrary to CP theory), consistency of action with the individual known conditions is not required.

So as with our discussion of the conjunction fallacy, we ask are there situations in organizational decision making where breaking the law of total probability might make sense? Take, for example, a large, mature organization which has a newly hired, enthusiastic marketing manager, who thinks that there is a need to re-energize and promote a brand with a new marketing campaign in order to increase sales revenue. A new campaign carries risk, until it has been tried and tested. Why should decision makers sanction a trial? If our marketing manager argues that the existing marketing campaign (A) does not generate the level of sales that the product should be achieving (∼X), decision makers in an organization suffering from inertia may still reject the marketing manager's proposal. For example, they may be emotionally committed to the existing campaign, they may feel that they have made a significant investment, and, finally, that the current approach is at least generating some revenue. Thus, they may elect to continue with the existing campaign (A). If the existing campaign (A) is generating an acceptable level of sales (X), then they will elect to continue anyway. Psychologically they may be suffering from the sunk cost fallacy (Arkes & Blumer, 1985) and may also fear reputational risk to themselves, if the new campaign fails. And of course there may also be other social, emotional and political forces at work (Hodgkinson & Healey, 2011; Teece et al., 1997; Tushman & Anderson, 1986) that are helping to maintain the status quo. At this point, with this example, all we have done is point out that an undesirable action, A, is likely to be adopted under both circumstances X and circumstances ∼X. Classically, by the law of total probability, the normative prescription requires us to adopt A, even when knowledge about X is lacking.

Some heuristic approaches, such as the failure of consequential reasoning principle in Shafir and Tversky's (1992) research, provide a descriptive account of violations of the law of total probability. However, such accounts do not allow us to overturn the interpretation of fallaciousness, which is the classically required characterization of violations of the law of total probability. We have argued that this is important, especially in situations in which there is a requirement for decision making to conform to a normative standard, that is, in situations in which reasoning has to be considered correct. But, if QP theory can be applied in the situation of interest, then decision makers can, correctly, reverse their action, when there is uncertainty about the critical information. The QP theory formulation resonates with Lewin's (1951) classic 3 step metaphor for change. The first step, unfreezing, involves the reduction of forces that are maintaining stability and introducing more uncertainty so that changes can be made.

In the case of our marketing manager, this means that he should not refer to the revenues associated with the existing campaign and whether or not they are acceptable. He might discuss alternative reasons, but, he should maintain uncertainty about the critical information. With an *absence* of the contextual information that is responsible for making people reach identical decisions, this allows for the possibility that reverse decisions will be made and a violation of the law of total probability. Note that, the standard intuition is that decisions should be made on the basis of availability of all necessary information; uncertainty generated by an absence of information would not be considered optimal or desirable. This is not to say that people can manage uncertainty in an optimal way. Indeed, people are generally uncertainty averse (Ellsberg, 1961; Epstein, 1999; Fox & Tversky, 1995) and uncertainty is regarded as an aversive state that people are motivated to reduce (e.g., Hirsch, Mar, & Peterson, 2012; Hogg, 2000; Weary & Edwards, 1996).

With the above thoughts in mind, one way to understand the QP formulation in more psychological terms is that perhaps contextual information anchors or forces the decision making process into inevitable directions. However, feelings of uncertainty have been shown to prolong positive moods and stimulate curiosity (Bar-Anan, Wilson, & Gilbert, 2009; Kurtz, Wilson, & Gilbert, 2007; Wilson, Centerbar, Kermer, & Gilbert, 2005). The absence of information, then, allows for additional perspectives in decision making and flexibility in thinking.

5. Organizational decision making and order effects

The complexity of real-life, organizational decisions means that decision makers frequently have to consider various pieces of information processed in a particular sequence. Different factors, such as social influence, politics or organizational procedures may determine the sequencing of information in the decision making process. For example, organizations often have to make decisions about their personnel as part of their selection and performance appraisal procedures. These types of decisions have been shown to be susceptible to the effects of interference between different variables in the decision making process (Highhouse, 1996, 2008; Thorsteinson, Breier, Atwell, Hamilton, & Privette, 2008). In assessment centers, which represent a common way of selecting new employees, contrast effects have been demonstrated, when there is a difference in performance levels between candidates, such that one candidate's performance can be rated as poor or strong depending on the performance of other candidates in the same exercise, even when the target candidate's performance is no different in either situation (e.g., Gaugler & Rudolph, 1992). Similarly, in performance appraisal, the procedures by which organizations evaluate employees can be subject to order effects generated by contrasting variations in performance between different employees (e.g., Palmer, Maurer, & Feldman, 2002).

The cognitive processes underlying such decision making can be viewed as heuristic processes taking place under conditions of uncertainty (Reb, Greguras, Luan, & Daniels, 2014). In particular, the order in which information is processed and decisions are made can influence the outcome. A study by Moore (2002), using Gallup polls, provides a good illustration of these ideas. Moore (2002) considered the same two questions, asked in two different orders, within a Gallup poll. For example, participants were asked the questions "Do you generally think Bill Clinton is honest and trustworthy?" and "Do you generally think Al Gore is honest and trustworthy" in either of two orders. When the Clinton question was first, 50% answered yes, when second 57%. When the Gore question was first and second, the corresponding percentages were 68% and 60%. The results partly suggest a process of assimilation, whereby the second question produces an answer which indicates a degree of consistency with the first (Moore, 2002). Psychologically, such results are intuitive. When a question is asked first, the person must rely on knowledge she can retrieve from memory related to the question. But, if this question is preceded by another one, then the person will incorporate some of her thoughts retrieved from the previous question into her answer for the second one (e.g., Schwarz, 2007).

According to CP theory, such order effects are fallacious. Consider two events, saying 'yes' to the Clinton question (Clinton) and saying 'yes' to the Gore question (Gore). Then, the classical description of the situation is that the probability of saying yes to Clinton and yes to Gore is the probability of saying yes to Clinton, followed by the probability of saying yes to Gore, given the Clinton answer. In other words, we have $\text{Prob}(\text{Gore}|\text{Clinton})\cdot\text{Prob}(\text{Clinton}) = \text{Prob}(\text{Gore}\&\mathit{Clinton}) = \mathit{Prob}(\text{Clinton}|\text{Gore})\cdot\text{Prob}(\text{Gore})$.
So, classically, it is an error if, across a sample of observers, the answers to the Clinton, Gore questions produce different probabilities (a classical model can be augmented with order parameters to numerically accommodate such results, but then the modeling framework becomes merely descriptive).

A QP model for question order effects (e.g., Wang & Busemeyer, 2013; for a simplified exposition see Pothos & Busemeyer, 2013) would assume that the possibilities that Clinton is honest and Gore is honest are incompatible, but also correlated with each other. Then, the answer to the two questions is a quantum conjunction, so that, depending on order, we would have either Prob(Clinton &then Gore) or Prob(Gore &then Clinton). Let us consider the second order. It is assumed that evaluating the Clinton question in isolation requires that Clinton is not considered particularly honest. However, having accepted Gore as honest creates an alternative perspective, from which Clinton appears more honest (because of the relation between the two candidates). It is as if the higher honesty of Gore somewhat transfers to a judgment about Clinton as well. This transfer is possible because Gore and Clinton would, in general, be perceived fairly similar, since they ran together.

Applying these QP ideas to the situation of personnel decision making suggests that, if you are evaluating the performance of Al and Bill, the rating for each might depend on whom you evaluate first. If you first consider Al, you are likely to incorporate some of the thoughts retrieved about Al into your evaluation of Bill. According to the QP model for order effects, such influences are likely to be generated, when there is some kind of connection between Al and Bill, for example, perhaps they work on the same team or on similar tasks. Note that, when a decision simply involves the rank ordering of two related options, then such order effects could be less of an issue. If you had to choose between just Al Gore and Bill Clinton based on how trustworthy you felt they were (cf. Moore, 2002), then whichever order you considered, Al Gore would have been selected. But, suppose additional options are included in the choice set, for example Lionel Messi, a candidate unrelated to Al Gore or Bill Clinton, who is therefore unlikely to influence the ratings of the two original candidates. Then, the actual rating of trustworthiness for each option does matter and so order effects could lead to inferior decision making, in that a factor irrelevant to the objective quality of the candidates (here, their order of evaluation) might affect the choice. For example, suppose that Messi is evaluated at 65%, Gore at 60%, when he is evaluated first, and at 68% when he is evaluated second. Clearly, whether Gore receives the top rating now depends on his assessment order, relative to Clinton.

No research, to the best of our knowledge, applying QP ideas to personnel evaluation has been carried out, although there are a number of empirical studies that suggest that QP might be a fruitful avenue for modeling the cognitive processes underlying performance appraisal. Order effects in evaluation are an obvious direction for further work, but there are other promising directions as well. For example, in research on the decision making of selection, the so-called decoy effect involves the introduction of a third option, which is dominated by only one of an existing pair of equal options. This can lead to decision makers favoring the dominating option (e.g., Highhouse, 1996; Huber, Payne, & Puto, 1982; Slaughter, Bagger, & Li, 2006), suggesting interference effects such as those typical of QP models. Dilution effects, whereby new, apparently irrelevant information, produces less extreme judgments (Nisbett, Zukier, & Lemley, 1981), may also influence performance appraisal (e.g., Reb et al., 2014) and be a good avenue of exploration with QP modeling. Furthermore, these types of effects are obviously not restricted to personnel decision making, but can equally be applied to other types of organizational decisions, such as the evaluation of different marketing campaigns for the same product or in strategic decision making when considering, for example, two separate, but related, markets (e.g., Korea and Taiwan). Our main point is that, typically, QP based models can plausibly accommodate effects, such as the ones described above and so offer insight into the underlying cognitive processes. For example, in the case of question order effects, the context created by the first judgment or piece of information that is processed alters the cognitive state and so interferes with the subsequent judgment; the advantage of using a QP model is that it allows a more detailed specification of the underlying representations and processes.

6. Intuition, superposition and the constructive nature of human judgment

It has been argued that whilst intuition can be fostered through experience, the development of expertise, and complex, domain relevant schemas, intuitive judgments themselves cannot be forced. Instead they happen instantaneously and involuntarily as a response to internal or external stimuli (Dane & Pratt, 2007; Hodgkinson, Langan-Fox, & Sadler-Smith, 2008). Given that intuition is, by its very nature, hard to explain rationally (Dane & Pratt, 2007), it might be a good candidate for a QP based approach. In this section, we consider a specific question in relation to intuition: does the transition from uncertainty about which response is appropriate, to the certainty associated with making the response, impact on the underlying representations?

A common assumption for many formal models used in decision theory, especially those based on CP theory, is that the cognitive system changes from moment to moment, but at any specific moment is considered to be in a definite state with respect to a decision to be made. Using QP theory the situation is different. QP allows the cognitive system to be in an indefinite or *superposition* state at each moment before the decision is made. This means that the cognitive system has the potential for any of the possible decisions at each moment in time, but which one is selected cannot be determined until the system is measured (e.g., the individual provides a response). This leads to a second important difference between CP and QP theory. According to models based on baseline CP theory, the measurement taken of a system at a given moment reflects the state of the system immediately prior to the measurement. However, in QP theory, taking a measurement of a system creates rather than records a property of the system (Peres, 1998), which means that the subsequent state of the cognitive system is constructed from the interaction between the superposition state and the measurement taken (Bohr, 1958).

White, Pothos, & Busemeyer (2013) and White, Pothos, and Busemeyer (2014) have provided an empirical demonstration of the influence that measurement can have on the cognitive system, using a simple two-step affective ratings task. In the first step, a positive (or negative) image was shown and in the second step an image made up of a combination of the first positive (negative) image and a negative (positive) image was shown. In a within subjects, counter balanced design participants rated the same second mixed images twice; after rating the first (single) image and after only viewing the first image without rating it. This enabled a within subjects comparison of ratings of the second mixed image, when participants had seen identical first images, presented in an identical order, with the only difference being the presence of an intermediate rating for the first image or not. Does this intermediate rating affect the second one? Baseline prescription from CP theory tells us that it should not (see also Hogarth & Einhorn, 1992, for the same prediction, on the basis of an alternative, standard framework). However, White et al. (2013, 2014) reported that the intermediate rating led to more negative ratings for the second image in the positive, negative order and vice versa (i.e., when the images were presented in a negative, positive order, an intermediate rating led to more positive ratings for the second image).

Psychologically, such results are not surprising. Several researchers have argued that making a choice can have a constructive influence, in relation to the underlying preference states. Simply put, the act of choosing an option can sometimes increase preference for that option (e.g., Ariely & Norton, 2008; Sharot et al., 2010; cf. Festinger, 1957). The intuition is that, in some cases, internal values do not exist. For example, the process of articulating a preference elaborates the relevant internal states so that, after the preference, these internal states are no longer the same.

Of course, many classical systems exist, such that making a choice can alter the relevant internal states. If we restrict ourselves to CP models, then a baseline assumption is that all uncertainty is epistemic, but internal values exist (it is just that we do not know what these values are). Therefore, the process of making a (non-invasive) measurement on the relevant states is simply one of reading off the internally existing values. One can certainly endow CP approaches with mechanisms which allow judgments to be constructive, but such mechanisms are additional components. By contrast, according to a QP approach, when the mental state is a superposition state, then a specific value for the corresponding choice or question does not exist. It is only through an act of measurement (e.g., an expression of a preference or decision), that a value comes to be.

Obviously not all judgments involve a constructive process, as for many cases there is a previously learnt response, which is simply retrieved at the point of measurement. However, for those types of loosely structured, ambiguous situations, which afford more complex, creative judgments, and which are more likely to feature intuition (e.g., Klein, 1998; Shapiro & Spence, 1997), QP may be a more natural method for understanding the cognitive processes involved in the transition from ambiguity to certainty. Prior to the decision, in QP terms, the individual is in an uncertain or superposition state, with respect to the decision being made. QP theory can provide a theory for the processes and related representations, as this (superposition) uncertainty is resolved and, more specifically, provide concrete predictions regarding the way constructive influences can arise.

7. Concluding comments

Research on decision making in organizations has generated many different theories and approaches based on heuristics (e.g., Gigerenzer, 1991; Gigerenzer & Todd, 1999), biases (e.g., Kahneman et al., 1982; Kahneman & Tversky, 1996), and socio-political influences (e.g., Cyert & March, 1963; March & Simon, 1958; Weick, 1995). There is general agreement that these approaches provide an accurate, ecologically valid, description of decision making in organizational and other real-life settings. Nevertheless, many still argue that models based on rational analysis and CP theory offer the best prescription for how decisions *should* be made. As a result, descriptive accounts of decision making based on, for example, heuristics, when compared against recommendations based on CP theory, can appear irrational or inaccurate. In other words, conjunctions between less and more probable events, uncertainty, or other interference effects in organizational decision making can lead to results which are hard to reconcile with the 'correct' predictions from CP theory.

Compared with rational analysis and models that use CP theory, QP models have been more frequently shown to be consistent with descriptive models and theories of organizational decision making. As it is possible to build normative arguments for QP theory, similar to those for CP theory (Pothos & Busemeyer, 2014), we suggest that, in some cases, QP theory can be used to justify decisions that would otherwise be considered fallacious and re-cast them as being formally correct (in QP terms).

We stated earlier in this paper that our work so far has been focused on evaluating the validity of QP cognitive models, against well-known empirical results. Indeed, much of the work in QP theory has focused on theory development and less attention has been given to empirical demonstrations. Equally, where empirical evidence has been gathered, it has focused on laboratory experiments; very little applied work has been carried out (for a notable exception see Wang, Solloway, Shiffrin, & Busemeyer, 2014). The objective of this paper is to explore whether the theoretical or research-oriented success of QP models can translate to implications for real-life organizational decision making. What have we learned about real life decision making from the QP cognition program? Our approach has been to provide a summary of our current work with QP cognitive models and so motivate a range of intuitive applications in organizational decision making. In other words, we have sought to generalize the lab-based, experimental situations, against which current QP models have been developed, to analogous real-life situations. We think that the generalizations we make are reasonable, nevertheless, at this point, inevitably they involve a fair amount of speculation too. Without direct experimental testing, it would be impossible to settle the case one way or another.

How might we go about testing some of our ideas in an applied setting? As reviewed in this paper, QP models can be tested using methodologies common to most judgment and decision making research. However, QP models also incorporate process assumptions. Thus, experiments that involve sequencing of information and varying requirements on timing of decisions could lead to strong tests of QP models. For example, the in-tray exercise, a management simulation used in assessment and management training, involves presenting participants with emails and memos concerning organizational issues and asking them to make decisions about those issues. Stimuli can be about different types of issues (e.g., strategic, operational, personnel). Stimuli are delivered either all together, where the ability to plan and prioritize is part of the assessment or sequentially, over the course of the exercise, so that adaptability can be assessed. So, for example, the exercise could enable tests of how a prior decision might influence a subsequent decision, as well as how the act of making a decision itself might influence later judgment. Another potential area for testing some of the process assumptions in QP models is the decision making of selectors working on an assessment center who, as a requirement of the assessment center procedures, will experience different sequences in the evaluation of candidates. Business simulations, a tool used in management development or case studies, a mainstay of business school education, may be useful ways of testing our ideas regarding the conjunction fallacy and law of total probability. For example, a business opportunity with a variety of characteristics might be evaluated, with a view to include characteristics which might lead to a conjunction fallacy or ensure the absence of certain information, so as to produce a violation in the law of total probability. Such experimental tests present us with an exciting direction for future research.

A source of optimism regarding this more applied direction of the QP research program is that the application of QP theory does not assume representational resources, which, in an applied setting, can be considered unrealistic. In CP theory, it is generally possible to construct a complete joint probability distribution, for arbitrary sets of possibilities (Griffiths, 2003, calls this the principle of unicity). But how realistic is this requirement? For example, in the case of Linda, classically, we need a complete joint probability distribution, not just for the properties of being a bank teller and a feminist, but for any arbitrary combination of properties, including ones which are rarely encountered together. It is unclear where the information for these joint probability distributions would come from. Moreover, there is an issue of computational complexity, since, for N binary possibilities, specification of the complete joint would require 2^N probabilities (and many more for the corresponding marginals). Such complexity may be beyond the capacity of the human mind (cf. Simon, 1955). Quantum theory avoids such problems and so perhaps provides a more natural framework for modeling human decision making, especially in applied settings. We hope that such a priori arguments, together with the directions we outlined in this paper, will help make the case that the development of QP cognitive models is a promising endeavor for modeling decision making in applied contexts of fairly direct practical significance.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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