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On the (Ir)relevance of Prospect Theory in Modelling Uncertainty in Travel Decisions

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This paper reflects on the relevance of prospect theory for transportation research. By discussing the original purpose and context of this theory of risky choice and the models that have been derived from the theory, the shortcomings and boundaries of the theory are discussed. It is argued that many applications in transportation and travel behaviour research may have stretched the domain of this theory too much, and that the theory lacks the necessary set of mechanisms and concepts to serve as a comprehensive theory of repeated travel choices under uncertainty. The discussion of shortcomings may serve to define a research agenda for further developing operational choice models.

Keywords: Prospect theory; Uncertainty; Travel choice

1. Introduction

The study of decision making and choice behaviour has a long tradition in a multitude of disciplines from mathematics to statistics, economics to political science and psychology to sociology. Seminal work on decision making under uncertainty can be traced back to Bernoulli (1738; see also Sommer, 1954) who offered an explanation why people are risk averse and why risk aversion decreases with increasing wealth. Compared to this more fundamental research, interest in decision making and choice behaviour in applied sciences such as marketing, urban planning and transportation is relatively new. It can be best characterized as attempts to apply existing theories of decision making, originally developed in other domains, or to develop operational models derived from such existing theories. In some cases, however, original theoretical contributions were also made.

The literature on decision making and choice behaviour can be distinguished into normative models and descriptive models (see e.g. Gärling, 1998 for a review for the transportation research community). Normative models are concerned with the question what choices people *should* make, assuming full rationality and the logic of decision making. Fundamental research has been concerned mostly with such normative theories. In contrast, descriptive analysis is concerned with people's decision making *as it is*, not as it should be. The second line of research is more relevant to transportation research. Various constructs, principles and models, based on

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particular theories have been formulated to predict and/or analyze preference formation and choice behaviour in a variety of application contexts.

Another important distinction is the difference between risky and riskless choice. Riskless choice refers to decision problems where the values of attributes of the choice alternatives are assumed to be (subjectively) known. In contrast, risky choices involve some probability that one or more attributes of the choice alternatives have a certain value or distribution, either objectively or subjectively. A distinction can be made between decision making under risk and decision making under uncertainty. In the former case, the probability distribution is known, in the latter case it is not.

In applied sciences, such as marketing, urban planning and transportation, the vast majority of studies on preference formation and choice behaviour has been concerned with riskless choice. Especially outside of transportation research, a large number of studies, based on a variety of theories, concepts, and measurement approaches has been suggested to analyze and model individual and household decisions. Figure 1 gives an overview of dominant approaches and key issues that have been addressed and explored in the early years (1970-1980s). These are listed in the context of a general conceptual framework that summarizes the common elements of the various approaches (Timmermans, 1982).

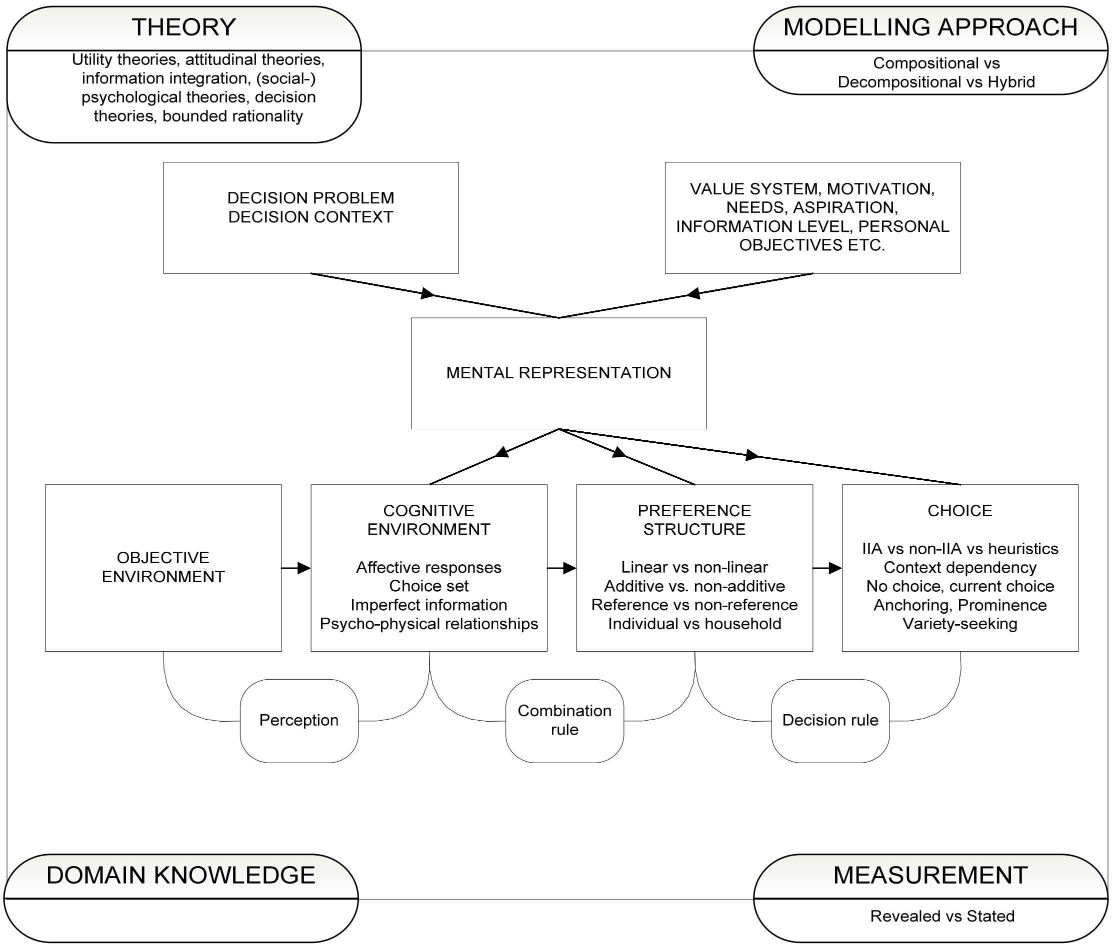


Figure 1. Conceptual framework and key topics in seminal behavioural analyses in marketing, urban planning and transportation research

Over the last decade, different theories and models of decision making under risk and uncertainty have been applied in transportation research, including expected utility theory (e.g. Bos *et al.*, 2004), mean-variance models (e.g., Sen *et al.*, 2001), regret theory (Chorus *et al.*, 2006a,b), random-regret minimization (Chorus *et al.*, 2008), and Bayesian Belief Networks (e.g., Sun *et al.*, 2009). (Cumulative) prospect theory (Tversky and Kahneman, 1979), the topic area of this special issue, is another theory that has been applied and tested in transportation research lately.

Not uncommon for applied sciences, fundamental discussions on the relevance of a particular approach are difficult to find in the transportation and travel behaviour literature. If the contention that human decision making varies by context, domain, and kind of problem is accepted, it is critical that researchers working in a particular domain of study systematically assess and compare the strengths and limitations of competing theories and models in terms of their face and content validity, predictive validity and sensitiveness to well-defined problems. In the context of transportation management, these problems include traveller response to travel information and (dynamic) activity-travel behaviour under uncertainty. At least two different approaches seem relevant: a comparison of alternative approaches, considering their potential shortcomings and a discussion of the boundaries of a particular theory.

Being asked to take a critical stance, in this contribution to this special issue on prospect theory, I will discuss some known and some new criticisms on prospect theory. and reflect on these from the perspective of the development of choice modelling in transportation research. In that context, it should be realized that the transportation research community has a rich set of alternative models that typically are not available in other disciplines. In that sense the value of prospect theory and any other theory does not only depend on domain-specific features of choice behaviour, but should also be judged in terms of its merits relative to competing theories. In this discussion, I will try to differentiate between boundaries and shortcomings. Several aspects of content validity will be discussed to explore the boundaries of (cumulative) prospect theory in travel behaviour research. In addition, because the use of prospect theory has typically been defended in transportation as an attempt to avoid the rational choice limitations underlying classical expected utility theory, I will argue that the typically (assumed) violations can for the most part also be captured by making appropriate operational decisions in currently dominant utility-based theories, many of which have in principle already been entertained in the stream of research illustrated in Figure 1. These can be seen as shortcomings that can be addressed in future research.

2. Formalism

Elaborating Liu and Polak (2007), assume that each decision maker i is faced with a set $C = \{\mathbf{s}^n;\ 1 \le n \le N\}$ of risky choice alternatives (prospects, lotteries). It implies that each prospect $\mathbf{s}^n$ in C itself consists of a set of J possible outcomes or states $\mathbf{s}^n = \{s_j^n; 1 \le j \le J\}$. Each outcome j of the nth risky prospect is defined by the values of a vector of observable attributes $X = \{x_k; 1 \le k \le K\}$, so that $s_j^n = (x_{j1}^n, x_{j2}^n, ..., x_{jK}^n)$. Associated with each risky prospect is a set of *given* probabilities $\mathbf{p}^n = \{p_j^n; 1 \le j \le J\}$, such that $\sum_{j=1}^{J} p_j^n = 1$, where p_j^n is the probability that outcome s_j^n is realised in $\mathbf{s}^n$.

Choice under risk implies that a decision maker has to integrate (i) information about the attributes characterising the outcomes and (ii) information about the probability of each outcome. We assume that each attribute k influencing outcome j of prospect n is valued according to mapping function h, which translates the values of the observable variables $x_{jk}^n; \forall j, k$ into valuation scores $v_{ijk}^{n};\forall j,k$. In turn, the valued variables are integrated according to function *g* to derive the valuation $v_{ij}^{n};\forall j$ of the *j*th outcome of the *n*th prospect. Thus,

$$v_{ijk}^{n} = h(x_{jk}^{n});\forall i,j,k \quad (1)$$

$$v_{ij}^{n} = g(v_{ijk}^{n});\forall i,j \quad (2)$$

Or, $$v_{ij}^{n} = g(h(x_{jk}^{n}));\forall i,j,k \quad (3)$$

Finally, we assume that the overall evaluation (or utility) u_{i}^{n} of prospect $\mathbf{s}^{n}$ by decision maker *i* is a function *f* of the valuations of the possible outcomes *j* of the *n*th prospect, the given probabilities of these outcomes $\mathbf{p}^{n}$ and a set of model parameters $\boldsymbol{\varphi}_{i} = \{\phi_{ir};1\le r\le R\}$ that characterise the decision making process in risky situations. Hence,

$$u_{i}^{n} = f(p_{j}^{n}v_{ij}^{n},\boldsymbol{\varphi}_{i};j=1,...,J) \quad (4)$$

2.1 Expected utility theory

The most *basic* version of expected utility theory (EUT), especially used in a normative context, is the expected value model, which states that the overall evaluation or utility u_{i}^{n} of prospect $\mathbf{s}^{n}$ by decision maker *i*, given $\mathbf{p}^{n}$ can be derived by taking the expectation of the outcome evaluations $v_{ij}^{n};\forall j$ over the

probability distribution $\mathbf{p}^{n}$. That is, it assumes that

$$u_{i}^{n} = \sum_{j=1}^{J} p_{j}^{n}x_{j}^{n} \quad (5)$$

More generalised functions are possible. Note that often a single outcome value is assumed. To link utility to choice, a decision rule needs to be specified. EUT assumes that an individual *i* will choose prospect $\mathbf{s}^{n}$ from choice set *C* iff

$$u_{i}^{n} > u_{i}^{n'} \quad \forall\mathbf{s}^{n}\neq\mathbf{s}^{n'}\in C \quad (6)$$

In other words, a deterministic decision rule is assumed in this classical case.

When applied in a non-normative context, several lines of research have been developed. Note that the prediction in the standard case depends on (a) *given* probabilities, (b) outcome values rather than the valuation of these values, and (c) deterministic decision rules. Each of these components has been relaxed/replaced. For example, in real-life, probabilities of outcomes will not be given, but have to be construed by individuals. It has been commonly assumed that to account for this difference, given objective probabilities can be replaced by subjective probabilities or beliefs $\mathbf{p}_{i}^{n}$, $\mathbf{p}_{i}^{n} = \{p_{ij}^{n} = \pi(p_{j}^{n});1\le j\le J\}$ where π is some probability weighting function, so that

$$u_{i}^{n} = \sum_{j=1}^{J} p_{ij}^{n}x_{j}^{n} \quad (7)$$

Secondly, rather than using the objective outcome values, the valuation of these values has been used. The prediction of the expected utility model then depends on the form of *h*(). Finally, the assumption of a deterministic choice rule has been replaced by various kinds of probabilistic choice rules.

2.2 *Prospect theory and cumulative prospect theory*

Kahneman and Tversky (1979) questioned the validity of expected utility theory, not as a normative theory, but rather as a descriptive theory of human choice behavior. It should be noted that this position relates to the basic form of EUT. As an alternative, they suggested prospect theory. In prospect theory, choice is based on transformed objective probabilities and outcomes as gains and loss. Let τ define a reference point in the outcome domain. Prospect theory then states that the utility of prospect n is defined as:

$$u_i^n = \sum_{j=1}^{J} \pi(p_j^n) h(x_j^n - \tau) \quad (8)$$

Prospect $\mathbf{s}^n$ is preferred to $\mathbf{s}^{n'}$ iff

$$u_i^n > u_i^{n'} \quad \forall \mathbf{s}^n \neq \mathbf{s}^{n'} \quad (9)$$

Compared to expected utility theory, prospect theory assumes that the decision process is divided into two stages: "editing" phase and "evaluation" phase. In the editing stage, gains and losses in the different options are identified, and defined relative to some neutral reference point so as to establish an appropriate reference point for the decision at hand. Gain refers to outcomes that exceed this reference point, while losses refer to outcomes that fall short. In the second stage, the evaluation phase, the decision maker evaluates the outcomes of each alternative by a value function and transforms objective probabilities into subjective probabilities by a probability weighting function. The value function is S-shaped and it is concave for gains and convex for losses. Kahneman and Tversky (1979) suggested the following functional form for the value function:

$$v_i^n(x_j^n - \tau) = \begin{cases} (x_j^n - \tau)^{\alpha} & if\,(x_j^n - \tau) > 0 \\ \lambda \,| x_j^n - \tau |^{\beta} & if\,(x_j^n - \tau) < 0 \end{cases} \quad (10)$$

Parameter $\lambda \geq 1$captures the degree of loss aversion, while parameters $\alpha, \beta \leq 1$ measure the degree of diminishing sensitivity to change in both directions from the reference point. The curves at zero, being steeper for small losses than for small gains implies loss aversion when outcomes are considered a loss and risk seeking when outcomes are considered a gain. As shown in Figure 2, this value function allows individuals to be risk-averse over gains but risk seeking over losses, with magnitude of losses higher than of gains.

The decision-weight function π is monotonically increasing, with discontinuities at 0 and 1, such that it systematically overweighs small probabilities and underweighs large probabilities. This allows the model to accommodate violations of expected utility such as the Allais and Ellsberg's paradox. Cumulative prospect theory (Tversky and Kahneman, 1992) extended prospect theory by including rank-dependent probabilities. It further allows for different probability weighting for gains than for losses (de Palma *et al.*, 2008). The main difference with Prospect Theory is that cumulative probabilities rather than the probabilities are transformed. Consequently, extreme events which occur with small probability rather all small probability events are overweighted.

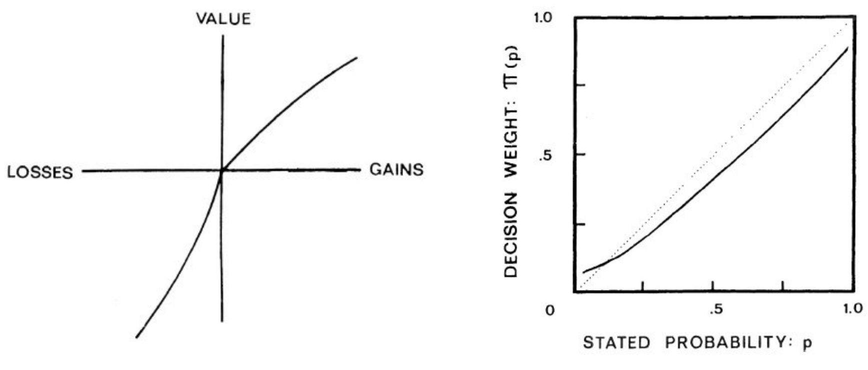
3. General criticism

3.1 Conceptual issues

Prospect theory assumes that decisions under risk and uncertainty are based on objective probabilities that are adjusted by applying decision weights. However, in situations other than those where information about objective probabilities can be provided, such as in gambles, individuals do not know these probabilities. Moreover, it is not very realistic to assume that they first assign probabilities and then apply some weighting scheme. Rather, imperfect and incomplete information about possible outcomes of uncertain events is reflected in beliefs. Applying decision weights to objective probabilities is merely a subjective expression of beliefs, which may not necessarily be systematically connected to the true randomness of the world. By own experience and through various other sources, people dynamically develop cognitive representations about their environment. For every decision problem, given the context of the decision, this cognitive representation is filtered. The filtered cognitive and/or affective representation constitutes the basis for judgments and decisions. Similar to the more advanced approaches for riskless decisions, shown in Figure 1, it may be conceptually richer to distinguish between mental representation, cognitive environment, preference structure and choice rule to avoid any confounding as potentially done in prospect theory.

For example, where prospect theory suggests that outcomes with small probabilities are overweighted, there is also evidence that in repeated choice settings, highly unlikely events with extreme outcomes are underweighted or even completely disregarded in updating (context-dependent) beliefs. This was also realized by Kahneman and Tversky (1979), who stated, "the simplification of prospects in the editing phase can lead the individual to discard events of extremely low probability and to treat events of extremely high probability as if they were certain. Because people are limited in their ability to comprehend and evaluate extreme probabilities, highly unlikely events are either ignored or overweighted and the difference between high probability and certainty is either neglected or exaggerated" (Kahneman and Tversky, 1979). However, they did not discuss the implications for the modeling process or the validity of the results.

Hertwig *et al*. (2004) argued that the apparent overweighting of small probabilities in gambling experiments may result from the fact that probabilities and possible outcomes are explicitly described to respondents, triggering specific response patterns. They show that in *decisions of experience* – when people do not have summary descriptions of the possible outcomes or their likelihoods and have to rely on their own experiences with a given situation – people tend to underweight small probabilities due to limited information search and overrating of recent experiences. If this findings can be generalized to transport decisions, it suggest that we learning



Value function Weight function

*Figure 2. Value function and weight function (*Kahneman and Tversky, 1979*)*

models for decisions under uncertainty may have more to offer than non-dynamic models of decisions under uncertainty such as (cumulative) prospect theory.

The problem is that in (cumulative) prospect theory risk attitude is nothing but a descriptive label of the curvature of the utility function and the weighted probability function presumed to underlie travel choices. Because there may be other good reasons for a nonlinear utility theory, the interpretation for nonlinear curvature may be difficult and not uniquely related to risk averse behavior. Moreover, as has been convincingly demonstrated in research depicted in Figure 1, as choices in certain real world environments do not necessarily reflect underlying preferences, observed choices in uncertain environments do not necessarily depict risk attitudes and corresponding decision styles. It cannot be ruled out that the characteristic curvature can be caused by mechanisms other than risk attitudes. As a theory of decision making under uncertainty for repetitive, routine-like choices, prospect theory lacks the behavioral concepts and may be too simple to avoid confounding of the various effects, shown in Figure 1, influencing the decision outcome.

3.2 Experimental effects

It is well-known that in general the validity and reliability of experimental data depend on (1) the motivation of respondents to fully participate in the experiment; (2) their comprehension of the task; (3) the lack of any bias introduced by the researcher, and (4) the congruence between the experimental task and actual decision making. Providing answers to hypothetical situations is not different from any daily decision. Respondents will make a mental representation of the hypothetical decision problem by processing the information and understanding the goal of the experiment. In this process, if they wish to please the experimenter, it is not unlikely that respondents try to guess the goal of the experiment and provide answers that are roughly correct given their anticipations of the underlying goal, but do not take too much time. If they only wish to marginally participate in the experiment, the processing of the information and the motivation to fully understand the experiment will be limited and respondents will respond quickly on the basis of the information that just caught their attention.

In conjoint analysis, later called stated preference and choice analysis in transportation researchers, professionally conducted studies involve various steps and design principles to maximize the validity and reliability of the measurements. Introductory examples are given to increase the subject's comprehension of the task. The wording and levels of the attributes are pre-tested. Profiles are generated to allow a critical test and unbiased estimate of an assumed preference function and choice model. Artificial non-linear utility functions are avoided by the choice of the right anchors/reference points. Randomization is used to avoid any confounding of non-manipulated effects. Effort is paid on understanding the relevant attributes and their levels, capturing the semantics used and making the experimental task natural and congruent with the investigated daily decision making process. The choices people need to make are similar or identical to their daily choices. In case of preference elicitation, it is realistic to assume that based on accumulated experiences and involvement in the topic under investigation, respondents have built up their preferences. The task of the experiment is to invoke a constructive process, triggering respondents to retrieve their preferences or apply their preference function to a set of carefully designed profiles. These profiles are chosen such that the responses are optimal with regard to some underlying criterion.

Compared to this state-of-practice, the experimental tasks used to test prospect theory typically look artificial. In some sense, many examples seem designed to articulate and amplify known biases as opposed to avoiding these. Experimental tasks often look like quizzes to test whether students understand expected utility theory. They require considerable processing of information and more importantly the *calculation* of losses and gains and overall payoff. Subjects may be unwilling or unable to calculate payoffs and certainly will make mistakes. The basis of responses in stated preference and choice experiments is the subject's memory and cognitive reasoning; the basis of responses in case of the gambling experiments are given probabilities and decision outcomes, how unrealistic they may be. Subjects need to process these artificial games, and their mental representation may differ from the constructed reality. It means that one cannot rule out the possibility that violations reflect incongruent mental representation and simple error as opposed to systematic bias.

Because prospect theory is largely based on experiments, evidence of risk aversion may have been confounded with errors introduced in understanding the experimental task, the framing of the task itself, limited information processing/bounded rationality in completing the task or any other process affecting the response-generating process. This problem is more general and occurs in any experimental task. Zhu and Timmermans (2009) argued that ideally the analysis of stated preference/choice data should include both a model of preference and choice behaviour, plus a process model of how subjects create a mental representation of the hypothetical choice problem. At the very least, it seems fundamental to compare prospect theory with competing theories for a series of alternative probabilistic choice rules to examine the robustness of the behavioural conclusions.

3.3 Assumption of deterministic utility function

Implicitly, prospect theory assumes that when faced with replicated identical binary choices, subjects will made the same choice. The reason is that the utility/value function is deterministic. There is overwhelming evidence however to the contrary. Camerer (1997), Hey and Orme (1994) and Ballenger and Wilcox (1997) to name a few report switching behaviour between 20 and 30%, fundamentally questioning the assumptions underlying prospect theory.

To translate inherently deterministic prospect theory into a stochastic array of observed choices, some transportation researchers (e.g. Schwanen and Ettema, 2007) have added an error term to the value function and assumed a utility-maximizing decision rule to derive a logit form model with a scale factor equal to 1. This set of assumptions is not very convincing. Not only is the use of an error term in conflict with the original theory, but assuming utility-maximization in the choice part and not in the valuing part seems inconsistent. Moreover, the results depend upon the assumed scale parameter of the utility function.

In disciplines other than transportation research, various probabilistic choice rules have been formulated and their specification is remarkably similar to progress in random utility theory/discrete choice models for riskless decisions. Adopting this approach, it is assumed that the decision theory is deterministic, but that in activating underlying utilities/value functions in experimental tasks and non-experimental, real world settings errors are being made. For example, a very simple rule may assume a constant reversal of deterministic binary choice patterns. Alternatively, homoscedastic random errors may be assumed. In the literature on decision making under risk this is known as the basic Fechner model, which of course is equivalent to the standard probit or logit model, depending on the assumed distribution of the error terms. In a transportation context, Avineri and Prashker (2005) also assumed that the probabilistic choice rule resulted in a logit-form probability of route choice behavior. Hey (1995) assumed heteroscedastic random errors to account for the notion that errors may depend on the number of possible outcomes, and the range of outcomes/utilities.

In the context of riskless choice, we have learned that the estimated parameters of a utility function depend on the assumed distribution of the error terms. One would expect this finding also to hold for decisions under uncertainty. It has important ramifications for the interpretation of results of prospect-theoretic models. The estimated parameters of prospect theory (and any other deterministic theory) may differ substantially depending on the assumptions that are made with respect to the stochastic choice rule that is assumed to capture the error-generating process.

There is no reason to rule out the possibility that this effect is so profound that wrong behavioural conclusions are drawn. Thus, evidence of risk aversion may vanish when a different stochastic choice rule is introduced.

An interesting study in this context was conducted by Blavatskyy and Pogrebna (2008) who found that expected utility theory with an expo-power utility function performed best of all decision theories tested when a constant error was assumed. Remarkably, cumulative prospect theory never outperformed other decision theories, regardless of the assumed probabilistic choice rules. Their results may be specific for their experiments, but the more fundamental issue remains.

Moreover, probabilistic choice rules would only allow for error in the activation of the underlying utility/valuing function. It does not imply however that risk attitudes are only captured in the curvature of the valuing function and decisions weights and not in the choice rule. There does not seem to be any inherent reason to assume that risk attitudes do not play a role in the choice stage of a decision problem.

3.4 Bias versus bounded rationality

Because prospect theory assumes a deterministic utility function and utility-maximizing behaviour, given the edited prospects, it implicitly assumes that individuals do take all information into account. However, many of the examined biases can also be explained by the alternative assumption that individuals demonstrate bounded rationality. They may filter attributes, set thresholds on attribute levels or may apply simplifying choice heuristics. One could argue that prospect theory is capturing this in the editing phase. However, the problem here is that prospect theory and cumulative prospect theory are difficult to test and apply in practice because the editing can be done in so many different ways, leaving many more degrees of freedom compared to other theories. This is understandable from the point of view that such flexibility is needed to explain different kinds of assumed biases in decision making, but it reduce content validity in the sense that the foundation of central behavioural principles and mechanisms that account for the larger spectrum of decisions is not necessarily attempted, perhaps as the result of searching for biases.

4. Applications in transportation research: relevant?

Before reflecting on the relevance of prospect theory to transportation research, I will briefly summarize some example applications. These serve to discuss the larger context. Some of these reflections may be relevant for other domains as well, while others may not.

4.1 Brief overview

Relatively late, in the early 2000's, transportation researchers started to explore the adequacy of (cumulative) prospect theory to predict traveller behaviour under uncertainty. Much of this research is concerned with preferred arrival times. Jou and Kitamura (2002) assumed two reference points: earliest acceptable arrival time and official work start time. Later, Senbil and Kitamura (2004) added preferred arrival time. Senbil and Kitamura (2006) incorporated delay /early arrival travel time variability directly in the utility function.

Schwanen and Ettema (2007, see also Schwanen, 2007) in a very similar effort but now related to picking up children at the day care also examined the role of reference points in a cumulative prospect model. Three reference points were used: (i) The time that most other parents pick up their child; (ii) the time imposed by the day care management that the children should be picked up, and (iii) the time that the day care officially closes. Note that their experiment differs from the usual meaning of the concept of framing, which implies an inherent equality. In their study, however, the different timing representations may capture different processes. Phrased as the time most other parents pick up their child indicates that the child may be left behind. The second time is heavily socially controlled and will trigger different processes. The third framing of time will cause serious problems for the parents themselves. In that sense the situation may be accumulative. A deterministic choice rule was assumed. Implicitly, this means that the authors assumed that the utility function is stochastic, theoretically violating prospect theory. Although the estimated models are limited in scope and surprisingly the parameters of the utility functions seem independent of socio-demographic variables, the models suggest that the value function is almost linear, while the loss aversion parameter is not significant. Although significant, the parameters for the decision weights suggest a slight overweighting of low probabilities. Overall, differences with expected utility theory seem modest at best.

Avineri and Prashker (2004, 2005, 2006) applied prospect theory in a route choice context. In their first study, respondents were invited to choose between different routes, characterized by different probabilities of travel times. They found evidence of non-linear decision weights and loss aversion.

Han *et al.* (2005) applied notions of prospect theory in a typical framing context. They assumed that travellers compliance rates with travel information does not only depend on the (in)congruence between the information provided and subjective beliefs, but also on the whether the information was provide din a positive or in a negative sense.

4.2 Conceptual limitations: incongruence in decision problem representation

Most empirical evidence supporting prospect theory is based on gambling experiments in which subjects are requested to choose one of two prospects, specifying the probability of associated outcomes. Thus, subjects are fully informed about all relevant attributes of the prospect, and moreover, the probability of possible outcomes is given. The question is whether this representation is valid for activity-travel decisions under uncertainty. In the context of the choice of departure time, route choice, etc. travellers will have more options. Consequently, the choice set may influence the decision making process under uncertainty. Consider the case of two prospects X and Y. Assume that given the specific framing employed, prospect theory suggests that travellers would be risk averse and choose the prospect with less risk, say X. However, now suppose that the value difference between these prospects increases. Then, there would be a point at which the travellers would be indifferent between the two prospects. Suppose in the experiment, a third option Z is included. It has a lower value than Y, but the risk is also lower. How would traveller behave under these conditions? Would they be more risk seeking and choose prospect Y because if they would fail, they still have the fall back position of Z?

The assumption of given probabilities is also incongruent with the typical decision problem in activity-based analysis. In general, travellers will not know the objective probability of an outcome. They can only sequentially experience outcomes over time, and they may filter, process and store these experiences in their memory and retrieve their memorized accumulated experiences when making decisions under uncertainty. Consequently, differentiation between decision weights and objective probabilities, as assumed by prospect theory, may be impossible.

A final source of incongruence is that uncertainty in prospect theory stems from the probability of outcomes. In contrast, in travel choices, uncertainty may arise from unfamiliarity with the choice alternatives and from uncertain events that are probabilistic in nature. Travelers are not always clear about existing alternatives, nor are they sure about the outcomes of some uncertain events in the transportation environment, mainly unforeseeable incidents, queues and congestion.

4.3 Conceptual limitations: ignoring credibility of information (source) and underlying control strategy

In classical prospect theoretical experiments the experimenter provides information about the probability of particular outcomes and the corresponding outcome value. The closest situation in travel behaviour seems the provision of travel information or recommendation. Still, this situation is fundamentally different in that travellers have to assess the value and underlying motives of the provided information. They may have reason to believe that the information or information source is not credible because (i) it may be based on imperfect model predictions or historical data, (ii) it may be not be real-time data, (iii) by the time they face the decision to make, the information may be old, and/or (iv) the information provider may have ulterior motives that may not necessarily be in the traveller's personal interest. For example, Han *et al.* (2008) found that subjects have the ability to decipher the nature of control strategies underlying information provision and act accordingly. To account for such effects, any comprehensive theory of travel behaviour under uncertainty should include principles and mechanisms how travellers develop beliefs about the credibility of the information and information source, how they learn about possible underlying control strategies and how they dynamically respond to information and recommendation provided under these circumstances. Standard (Cumulative) prospect theory does not satisfy this criterion.

4.4 Conceptual limitations: ignoring learning effects

The typical examples providing evidence for the validity of prospect theory typically involve one-shot decisions. Departure time, route and destination choice differ fundamentally from the typical gambling problem in that travellers experience the consequences or outcomes of their decisions, and more importantly can adapt their behaviour to influence the experienced outcome. Prospect theory does not take such feedback and consequent learning and adaptation into account. However, loss aversion implies that travellers will likely experience that they could have done better. Repeatedly using updated reference points will then, ceteris paribus, lead to decisions and choices that deviate from the predictions of standard prospect theory. Loss aversion does not seem an effective coping mechanism against regret! One would expect that the value function becomes less curved as uncertainty is reduced, reflecting proportionally less concern with small gains and losses with larger change. This process may be captured at the level of the value function, but it may also involve ignoring extreme outcomes in the mental representation of the decision problems and updating of beliefs, implying that the value function will be activated for a small domain only in which its curvature is (almost) linear.

Similarly, loss aversion does not seem an effective behavioural mechanism in case of information exchange and common attitude formation in social networks. The idea that they can do better may trigger a process of exploring new options, which in turn may lead to improved strategies.

(Cumulative) prospect theory has little to say about how travellers learn and adapt their behaviour to the structure and dynamics of a given uncertain environment and to varying degrees of awareness, information levels and belief strengths.

4.5 Conceptual limitations: gains and losses

Prospect theory assumes that people use reference points to differentiate between gains and losses and that the curvature of the value functions differs between gains and losses. In the gambling experiments, a natural reference point is whether or not people would win or not when bidding. To accommodate status quo, endowment and other phenomena, Tversky and Kahneman (1979) indicated the reference points or states could also be influenced by aspirations, expectations, norms and social comparisons. Conceptually, a definition of reference points in those terms is very similar to a substantial amount of research on riskless choice in which the utility of an alternative has been specified against the utility of the current situation.

The definition of a reference point in travel behaviour is far from evident. Fundamental to prospect theory is the notion that people consider gains and losses in making risky decisions rather than total wealth. While this may be a defendable proposition for some decision problems, the question is whether loss aversion also plays a significant role in routine behaviour such as departure time, route and destination choice. Is time allocation to travel and different activities better conceptualized in terms of gains and losses are just as alternative choices? Time serves as a proxy for the pleasure or need to conduct activities, including travel.

Shouldn't the application of the theory be restricted to decisions under risk that involve true significant, irreversible losses?. In the context of departure time, this conceptualization seems less appropriate: even if travellers would view late arrival as a loss, the consequences can be easily remedied by calling ahead, working more efficiently or appealing to the largely accepted excuse of congestion for being late.

There is also the issue of immediacy. Empirical studies have shown that when subjects gamble and are offered immediate payment of any monetary gains, they tend to be risk averse. However, if the outcome and payment will be in some future point in time, they tend to be much less risk averse under the same experimental conditions. In travel behaviour context, travellers will hardly ever receive any immediate gains for their travel choices in this sense.

Perhaps the most important feature that makes prospect theory different from other theories is the different curvature of the value function for gains and losses. Although non-symmetrical continuous functions could at least approximate the concavity/convexity of the function for gains and losses, the explicit differentiation of the two domains of the function offers substantial flexibility to the researcher and a higher chance of improved fit because simpler functions are special cases. However, this potential benefit is significantly less if the decision problem can be realistically conceptualized in gains or losses only. Consider the departure time problem. Using prospect theory, the problem has been conceptualized in terms of late respectively early arrivals. However, both can be viewed as losses (negative utilities) and can be captured by a similar utility function for the disutility of early arrival and the disutility of late arrival, if one is not willing to view travel decisions as a time allocation problem.

In any case, reference points are not exogenously given, except in the case of travel information. Travellers may endogenously use reference points to value attributes and make choices. For example, in the context of departure choice, several definitions of arrival times as reference points have been used. In case of route choice, Avineri and Bovy (2008) argued that one may assume that reference points are related to the median or mean travel time experienced in the population of the target traveller group. Behaviourally, this does not seem a valuable proposal as most travellers will not know these travel times, but need to rely on own experiences, unless it is based on information disseminated through their social network, which however then should also be modelled. Avineri (2009) suggested to apply fuzzy reference points. Travel time experiences will vary and travellers will try to explain such variability by developing a mental causal network that accounts as much as possible for such variability. Hence, reference points are likely context-dependent and will vary between travellers. However, in case of well-articulated beliefs about the distribution of travel times, it is not readily evident why travellers would not directly act on their context-dependent beliefs of travel times and risk attitudes, rather than first processing and valuing travel time variability against some endogenous reference point. It is even more likely that they have built up strong beliefs about the effectiveness of departure time strategies, skipping processing of travel time information altogether. The chosen or best alternative, given the travellers' risk attitude may then serve as a reference point to scale alternative options or to assess new options under traveller information or unexpected events. In this case however the domain of loss versus gain will be automatically given, meaning that the concept of a reference point has lost its strict meaning.

Using principles of bounded rationality, Zhu and Timmermans (2010) have argued that travellers may use multiple reference points. In their conceptualisation, however, reference points do not serve as anchors to distinguish between gains and losses, but rather as thresholds for accepting a decision strategy or not. For example, travellers may mentally use multiple reference points to accept or reject a particular decision. These reference points vary as a function of time, updated information and involvement in the decision. Choice options in their model are judged on the basis of their consistency against multiple thresholds.

Based on this brief literature review, it seems that transportation researchers have primarily explored the applicability of (cumulative) prospect theory to incorporate reference points in their models to differentiate between gains and losses. It should be recalled, however, that the use of reference points or thresholds has a long history in modelling riskless choices to model ideal points in attribute evaluations, variety seeking behaviour, inertia/status quo, hybrid utility functions and choice rules, aspects of bounded rationality, relative utility theory (Zhang *et al*., 2004), historical disposition (Chen *et al*., 2008; Habin and Miller, 2009) and different frames of references as a function of accumulated experiences (Borgers *et al*., 2007). Hence, choosing prospect theory because the researcher feels a reference point is necessary is not necessarily an adequate reason as several other utility-based alternative theories have been shown to offer the same mathematical functionality.

5.6 Conceptual limitations: heterogeneity and context effects

As shown by Figure 1, the literature on riskless choices has identified a series of effects influencing riskless choice behaviour, including effects of choice set, context, and taste variation to mention a few. In turn, these factors have been incorporated in increasingly more complex choice models and modeling approaches. Polak *et al.* (2008) have extended this to expected utility theory. (Cumulative) prospect theory does not take these effects into account. However, there is no reason to assume that these effects are not equally relevant for choice under uncertainty. Moreover, applications of prospect theory have tended to be restricted to departure time and route choice under a single source of uncertainty. However, travel time uncertainty is not restricted to a certain link of a path, but multiple sources of uncertainty may occur, some of which may be shared by different routes. Furthermore, departure time and route choice are just part of daily activity-travel scheduling processes and should be modeled accordingly.

5. Conclusion and discussion

The purpose of this paper has not been to downplay in any way the importance in general of (cumulative) prospect theory. Although in my opinion the rhetoric surrounding prospect theory is somewhat reminiscent of Don Quixote and much experimental evidence is questionable at least, the theory did draw the attention to some key aspects of risky choice behavior. Moreover, the well-articulated and appealing arguments did lead to an impressive amount of research in a multitude of disciplines. In that sense, (cumulative) prospective theory is one of the leading theories of decision making under risk. My role was primarily to stimulate the discussion by (over-)emphasizing certain issues. I think that prospect theory has been applied in transportation research mainly in a technical way and that consequently it is important to reflect on the potential boundaries and shortcomings of the theory and the applications to (1) formulate a research agenda for modeling transport choice under uncertainty, and (ii) identify the problems for which (advanced) prospect or other models are appropriate and the problems for which alternative theories have more to offer.

The motivation underlying this paper is to explore the shortcomings and boundaries of prospect theory especially in the context of modeling travel behavior under uncertainty. To that end, the paper has systematically examined aspects of face and content validity of (cumulative) prospect theory as a *theory of travel behavior* under uncertainty. I have argued for some fundamental differences between simple gambling behavior under risk and complex travel behavior under uncertainty. Some empirical regularity may be captured well by the nonlinear, referenced-based curvature that is associated with cumulative prospect theory. Many of these mathematical functions however have been applied before as part of competing modeling frameworks or can be used in that context without conflict. Whether prospect theory (and any theory for that matter) is only characterized by the curvature of the mathematical equations may be open to debate; I would argue that there is still the issue of content validity. This discussion about the concept and mechanism included and not included may serve to reflect on the boundaries of prospect theory as a theory of travel behavior under uncertainty.

I have also discussed some aspects of travel behavior research under uncertainty that are poorly addressed by prospect theory or not addressed at all. These can be seen as shortcomings that can be addressed in future research and thus make a research agenda for transportation researchers. Although prospect theory has been highly instrumental in identifying potential biases in (risky) decision making processes, the 35 years since its introduction have not led to the development of sophisticated operational models. Systematically dealing with taste variation and including several effects that influence the choice phase of the decision making process are some examples. In general, the literature on prospect theory tends to focus on hypothesis testing as supposed to model development and estimation. There is an inherent tendency to amplify anomalies. Even if these would occur systematically, this does not necessarily mean that they are influential in the overall decision making process, nor that most progress in developing operational models of (dynamic) travel behavior under uncertainty is made by addressing these biases. As the current research frontier suggests, progress made in the context of riskless discrete choice theories can be incorporated in prospect-theoretical models, ultimately leading to the blending of advanced utility theory and prospect theory. Whether one would still call this prospect theory (or modern utility theory under uncertainty) is not very clear and may be a matter of opinion. In the end, such a discussion would not even be relevant. Given the current state of development such models would rely more heavily on advanced discrete choice theory than on prospect theory. However, although all these lines of research should be pursued, the conceptual richness, the congruence of assumed causal mechanisms and structures, and the content validity of these models as a manifestation of a theory of travel behavior under uncertainty is relatively poor compared to competing theories of travel behavior under uncertainly, such as (Bayesian) network learning models, and regret-theoretical approaches. These competing approaches are not more or less direct applications of theories originally developed in other domains, but try to develop a domain-specific modeling approach based on the salient features and key underlying processes of activity-travel behavior under uncertainty. Making travel decisions under uncertainty is not even close to gambling for money!

The ultimate relevance of prospect theory for travel behaviour research therefore depends on the specific application. Prospect theory was originally designed to explain responses to *static* situations involving risk, in the lack of immediate feedback and repeated choices. It may therefore be a superior and certainly a highly relevant approach for pricing studies, as it has been in marketing, to examine and predict the effects of framing on choice behaviour. It may be relevant in modelling traveller short-term reaction to prescriptive, credible, personal travel information. However, at the current state of development, it lacks the rigor, scope, behavioural principles and mechanisms, and content validity to serve as a comprehensive theory of how individuals and households dynamically (re-)organize their activities and travel (departure, route choice, destination, transport mode decisions) along multiple horizons in uncertain, non-stationary environments in a ubiquitous information society, enforcing a diversity of travel control strategies, for which they can rely on past experiences. Applications of (cumulative) prospect theory to these types of choices represent an attempt to apply the theory in the wrong contexts.

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