Journal of Theoretical Biology 404 (2016) 222–235

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

Scalar utility theory and proportional processing: What does it actually imply?

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HIGHLIGHTS

- Scalar Utility Theory (SUT) predicts choice behaviour in context of variable rewards
- We show that: (1) SUT implies violations of several concepts of rational behaviour
- (2) SUT implies varying risk preferences for both reward amounts and delays to reward
- (3) SUT and coefficient-of-variation model of risk sensitivity both con- and di-verge
- In addition, a straightforward way to test the key assumptions of SUT is suggested.

ARTICLE INFO

Article history:
Received 13 March 2016
Received in revised form
31 May 2016
Accepted 1 June 2016
Available online 8 June 2016

Keywords:
Scalar expectancy theory
Scalar property
Weber's law
Decision making
Risk preferences

ABSTRACT

Scalar Utility Theory (SUT) is a model used to predict animal and human choice behaviour in the context of reward amount, delay to reward, and variability in these quantities (risk preferences). This article reviews and extends SUT, deriving novel predictions. We show that, contrary to what has been implied in the literature, (1) SUT can predict both risk averse and risk prone behaviour for both reward amounts and delays to reward depending on experimental parameters, (2) SUT implies violations of several concepts of rational behaviour (e.g. it violates strong stochastic transitivity and its equivalents, and leads to probability matching) and (3) SUT can predict, but does not always predict, a linear relationship between risk sensitivity in choices and coefficient of variation in the decision-making experiment. SUT derives from Scalar Expectancy Theory which models uncertainty in behavioural timing using a normal distribution. We show that the above conclusions also hold for other distributions, such as the inverse Gaussian distribution derived from drift-diffusion models. A straightforward way to test the key assumptions of SUT is suggested and possible extensions, future prospects and mechanistic underpinnings are discussed.

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1. Introduction

Ernst Heinrich Weber (1795–1878) was one of the founders of psychophysics. Weber's law states that the resolution of perception diminishes in proportion to the magnitude of the stimulus. That is, if a just noticeable difference between a 10 kg weight and another weight is 10γ kg, where γ is a positive constant, then only differences exceeding 20γ kg can be detected when comparing a weight to a 20 kg weight. Drawing on a body of previous theory (e.g., Gibbon, 1977; Gibbon et al., 1988), Kacelnik and Brito e Abreu (1998) used Weber's law to propose that the representation of a stimulus of magnitude m in an animal's memory has an error distribution that is Normal with mean m and standard deviation γm, denoted $N(m, \gamma m)$; a theory now known as Scalar Utility Theory, or SUT (Kacelnik and El Mouden, 2013; Marsh and Kacelnik, 2002). The "scalar" parameter γ is a species and stimulus-type (but not stimulus-quantity) specific constant that captures the general resolution of perceptual memory. SUT is a generalization to both delays to reward and reward amounts of the original model for delays only, known as Scalar Expectancy Theory (Gibbon, 1977).

SUT has had some notable success in explaining effects of risk in decision making (Bateson and Kacelnik, 1995a, 1995b; Brito e Abreu and Kacelnik, 1999; Buhusi and Meck, 2005; Kacelnik and

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http://dx.doi.org/10.1016/j.jtbi.2016.06.003
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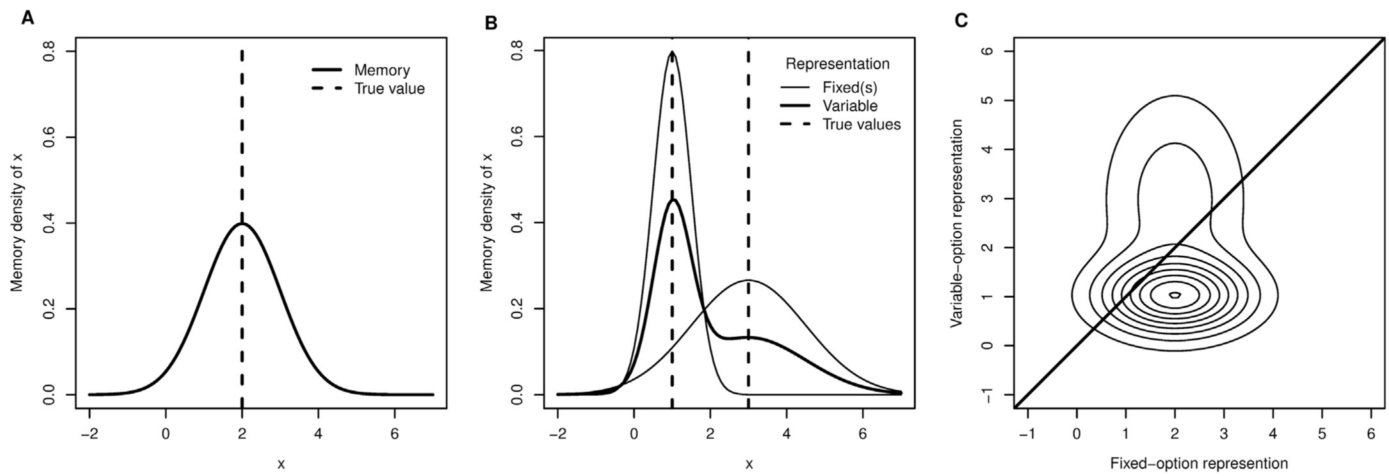

Fig. 1. Typical application of Scalar Utility Theory (SUT). A) If an animal has been trained in an experiment where a choice option always delivers a reward of magnitude 2 (vertical dashed line), the animal's operational (memory) representation is approximated by a normal distribution with mean 2 and standard deviation $\gamma 2$ (solid line for probability density function; $\gamma = 0.5$ here). B) When a choice option yields a reward of 1 with probability of ½ and a reward of 3 with probability of ½ (mean is again equal to 2), then this option's representation is assumed to be a mixture of the representation (thick line) for the equivalent certain rewards (thin lines), with the mixing weights equal to the probabilities of respective cases of reward in the experiment: (½,½). Because the standard deviation of mental representation of a reward is assumed to be proportional to the reward value, a more dispersed representation for the bigger outcome is superposed on a less dispersed one for the lower outcome, which induces a skewed representation for the variable reward. C) Contours of the joint distribution of the independent fixed (horizontal axis) and variable (vertical axis) choice options. Because of the skew for the variable option and equal means for the fixed and variable option (i.e., 2), a larger share of the probability mass resides below the diagonal; i.e., in the set {fixed option > variable option}. Thus, in independent random samples the event {fixed option > variable option} occurs more often, implying risk-averse behaviour for variable reward amount.

Bateson, 1996; Reboreda and Kacelnik, 1991; Shafir et al., 2008), but has received surprisingly little theoretical attention since the seminal work of Gibbon (1977) and Gibbon et al. (1988), despite the rapidly accumulating empirical data. Therefore, we provide an updated theoretical review and summary of the predictions of SUT and dispel some common misbeliefs regarding them. We specifically concentrate on the challenge posed for future research in a recent review of proportional processing: "… to model what behaviour influenced by proportional processing would look like …" (Akre and Johnsen, 2014).

A central goal in the study of animal and human behaviour has been to understand risk sensitivity in choice preferences (see Kacelnik and El Mouden, 2013; Rieskamp et al., 2006, for reviews). Some researchers approached the problem through functional explanations, deriving models that explain what kind of state-dependent risk sensitivity should evolve by natural selection (Caraco et al., 1980; Barnard et al., 1985; McNamara and Houston, 1992; Houston and McNamara, 1999). While theoretically justified, the models failed to explain the ubiquitous partial preferences of animals (variable choices in the same task despite the same conditions; McNamara and Houston 1987; Shapiro et al., 2008). By reference to findings of psychophysics, SUT and its precursors were able to propose a proximate mechanism that intrinsically explains both the partial preferences and the findings on risk sensitivity reviewed below (Gibbon et al., 1988; Reboreda and Kacelnik, 1991; Kacelnik and El Mouden, 2013). However, SUT does not explain switches in risk sensitivity as a function of the external environment and the animal's internal state (Caraco et al., 1980; Houston and McNamara, 1999).

Researchers since Tinbergen (1963) have recognised the need to integrate the levels of explanation (Kacelnik and Bateson, 1996; Kacelnik and El Mouden, 2013; McNamara and Houston, 2009). Provided that our curiosity is not satisfied by a simple statement that all the levels are likely to play a role, such integration requires an understanding of the fundamental components to be integrated. This paper aims to contribute to this wider discussion by improving the level of theoretical understanding about the implications of SUT.

A paradigmatic application of SUT involves understanding an animal's behaviour when it is forced to choose between two options with the same arithmetic mean, one having no variance ("fixed" or "safe" option) and the other ("variable" or "risky" option) involving either a variable amount of reward or variable delay to reward (e.g. Bateson and Kacelnik, 1995b; Kacelnik and Brito e Abreu, 1998; Kacelnik and El Mouden, 2013). Simple arguments that identify the value of an option with its arithmetic mean suggest that animals should be indifferent in such experiments, but instead, they are typically found to favour the variable option for delays in reward and often prefer the fixed option for reward amounts (Kacelnik and Bateson, 1996; Kacelnik and El Mouden, 2013). It has been thought that this constitutes broad support for SUT, but despite many empirical studies, researchers have not carefully outlined the theoretical predictions of SUT, apparently thinking that the general trends of risk proneness for delays and risk aversion for amounts are what SUT predicts (Kacelnik and Bateson, 1996, 1997; Kacelnik and Brito e Abreu, 1998; Kacelnik and El Mouden, 2013). Here we outline the fuller flexibility of the model's predictions, providing a possible basis for resolution of conflicts, as well as new ways to support or disprove SUT experimentally. We also make connections with related literature.

This paper is organised in the following manner. First we explain and define the SUT model. Then we outline its, often surprising, predictions in a number of different contexts. Specifically, we consider previously misrepresented model predictions of SUT, different accounts of rational decision making in the context of SUT, and efficient ways to test SUT. After this section on model predictions, we discuss extensions, future prospects, and mechanistic underpinnings of SUT, and then conclude the paper.

1.1. The model

1.1.1. Basic definitions

SUT is a model of perceptual memory's accuracy that is to be applied only after the animal's learning process can be considered as having stabilised in the sense that further experiences of the same experimental setting no longer change the expected behaviour (i.e., observed behaviour is stationary, but some learning processes may well be in operation). Pertaining to the paradigmatic application of SUT, Fig. 1A shows how SUT assumes that the

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