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RESEARCH ARTICLE

Impulsivity modulates performance under response uncertainty in a reaching task

C. Tzagarakis · G. Pellizzer · R. D. Rogers

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Abstract We sought to explore the interaction of the impulsivity trait with response uncertainty. To this end, we used a reaching task (Pellizzer and Hedges in Exp Brain Res 150:276–289, 2003) where a motor response direction was cued at different levels of uncertainty (1 cue, i.e., no uncertainty, 2 cues or 3 cues). Data from 95 healthy adults (54 F, 41 M) were analysed. Impulsivity was measured using the Barratt Impulsiveness Scale version 11 (BIS-11). Behavioral variables recorded were reaction time (RT), errors of commission (referred to as 'early errors') and errors of precision. Data analysis employed generalised linear mixed models and generalised additive mixed models. For the early errors, there was an interaction of impulsivity with uncertainty and gender, with increased errors for high impulsivity in the one-cue condition for women and the three-cue condition for men. There was no effect of impulsivity on precision errors or RT. However, the analysis of the effect of RT and impulsivity on precision errors showed a different pattern for high versus low impulsives in the high uncertainty (3 cue) condition. In addition, there was a significant early error speed–accuracy trade-off for women, primarily in low uncertainty and a 'reverse' speed–accuracy trade-off for men in high uncertainty. These results extend those of past studies of impulsivity which help define it as a behavioural trait that modulates speed versus accuracy response styles depending on environmental constraints and highlight once more the importance of gender in the interplay of personality and behaviour.

Keywords Impulsivity · Uncertainty · Reaching · Barratt impulsiveness scale · Gender differences

Abbreviations

BIS	Barratt impulsiveness scale
RT	Reaction time
ADHD	Attention deficit hyperactivity disorder
GLMM	Generalized linear mixed model
GAMM	Generalized additive mixed model
REML	Restricted maximum likelihood

Introduction

Psychiatrists and lay people alike often describe impulsive people as those who 'act before they think'. In other words, impulsivity conjures up the image of premature, poorly considered action, dissociated from deliberative decision-making. Impulsivity, understood in this way, is believed to be a trait that underlies a great deal of debilitating psychopathology (Moeller et al. 2001). Disorders including bipolar affective disorder, borderline and antisocial personality disorders and ADHD all list impulsivity among their defining characteristics. Whilst these conditions are clinically very different, affected individuals tend to be characterised by their impulsiveness and to suffer the undesirable consequences of impulsive actions. This

C. Tzagarakis (✉) · R. D. Rogers
Department of Psychiatry, Warneford Hospital,
University of Oxford, Oxford OX3 7JX, UK
e-mail: haristz@umn.edu

C. Tzagarakis · G. Pellizzer
Department of Neuroscience, University of Minnesota,
Minneapolis, MN 55455, USA

C. Tzagarakis · G. Pellizzer
Brain Sciences Center, Veterans Affairs Health Care System,
Minneapolis, MN 55417, USA

common understanding of impulsivity as a simple dimension of action has been all but obscured by efforts to define it in terms of a comprehensive psychological construct. Formal psychometric conceptions of impulsivity implicate a range of different mental operations that include attention, reward processing, response inhibition and probability, as well as response selection (Evenden 1999). In turn, this has given rise to multiple performance instruments to evaluate impulsivity—each one addressing a slightly different facet of the construct. These include, the 'go/no-go' (Bezdjian et al. 2009), continuous performance (Dougherty et al. 2000) and 'stop-signal reaction time' (Logan et al. 1997) tasks that focus on different aspects of the ability to inhibit a prepotent response, timing-specific tasks (Wittmann et al. 2011) as well as a variety of 'delayed discounting' tasks focusing on the impulsive tendency to under-value larger rewards if they are delayed (Peters and Büchel 2011). Similar tasks (Winstanley 2011), of which the most well known is probably the 5-choice serial reaction time task (Robbins 2002), are widely used in animal studies of impulsivity to investigate its neural substrates.

These approaches to the investigation of impulsivity tend to focus on the effects of impulsivity in situations where the repertoire of actions is stable (albeit sometimes variably weighed). However, they do not easily lend themselves to examining the potentially differential effects of impulsivity when available options change constantly in response to changing environmental conditions. And yet such situations are frequently observed in real life. In circumstances where impulsivity is responsible for 'actions that are then regretted' there are de facto always more than one course of action to consider without necessarily sufficient clarity as to what those might be. Such fluctuating environmental conditions that involve selections between different (and variable) candidate actions naturally introduce uncertainty in choice and action, and impulsivity may differentially influence the control of behaviour under such circumstances (Evenden 1999; Leland et al. 2006). For these reasons, in this experiment, we sought to explore the joint influence of impulsivity and uncertainty in planning and subsequent action. To this end, we used a cued reaching task (Pellizzer and Hedges 2003) where variability in the numbers of cues given allowed to modulate uncertainty about the upcoming reaching act. It is well known that in such tasks reaction time increases with uncertainty. We wanted to investigate how task behaviour (reaction time and errors) is further modulated by varying levels of trait impulsivity. Specifically, we hypothesised that the increased burden of higher uncertainty might be further potentiated by high impulsivity and translate to even higher reaction times at elevated uncertainty as impulsivity increases. In addition, errors linked to early commitment to a motor act should be higher for impulsives according to past prepotent response inhibition findings but also decrease with increasing uncertainty. Finally, the indications of as yet not much explored gender differences in impulsivity found in the literature (Trent and Davies 2012) allowed for the expectation of an effect of gender in our results.

Materials and methods

Datasets

The study protocols were approved by the University of Oxford Research Ethics Committee. Participants gave informed consent and were recruited through advertisement in the local press as well as posters placed in University common areas. Data were collected from 95 healthy adults (54 women, 41 men, 93 right-handed, 2 left-handed) with a mean age of 24 years (range 18–38 years). Part of the data was obtained whilst subjects participated in a magnetoencephalography study (30 women; 25 men) and another part from subjects participating in a regular psychophysics study (24 women; 16 men). For the purposes of random effect analysis, these 2 datasets were coded as 'sub-sample 1' and 'sub-sample 2', respectively. Exclusion criteria were the presence of diagnoses of active mental illness, and/or substance addiction (drugs and/or alcohol), as well as the use of psychoactive medication. Participants completed the Barratt impulsiveness scale (BIS-11) (Patton et al. 1995). This is a scale with a long development history that provides a robust self-report measure of impulsivity. The total Barratt scale scores in our sample ranged from 38 to 96 with a mean BIS score of 62 and a standard deviation of 11.8, which is consistent with population normative data for the scale (Spinella 2007). There were no significant gender differences as regards age or BIS score in the sample (all one-way ANOVA F tests with $p > 0.05$).

Experimental procedure

Participants performed an instructed-delay reaching task with different degrees of uncertainty about the location of the upcoming target (Pellizzer and Hedges 2003).

Figure 1 shows the sequence of events in a typical trial. During the task, the participants, using a joystick controlled with their preferred hand, initiated a trial by placing a cursor within a circular window in the centre of the display for a 3-s centre-hold period. The subjects were instructed to fixate the centre of the display during the centre-hold and until the end of the trial. The centre-hold period was followed by a cue period that varied randomly between 1.0 and 1.5 s, after which the target was presented. During the cue period, one, two, or three white circles indicated the

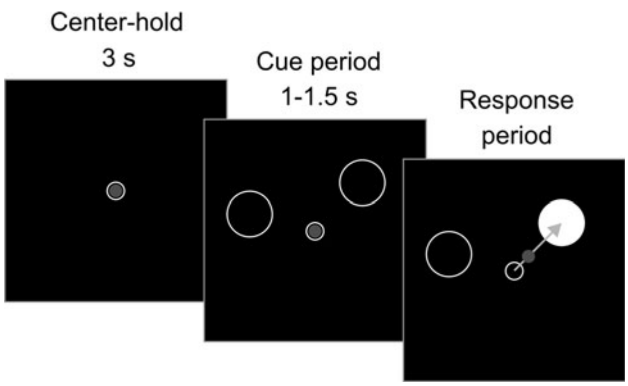

Fig. 1 Schematic representation of a typical trial. Participants controlled a cursor using a joystick. To initiate a trial, they had to place the cursor within a *circular* window in the *centre* of the display for a 3-s centre-hold period. The centre-hold period was followed by a cue period in which one, two, or three *white circles* indicated the location(s) at which the target might appear. The cue period varied randomly between 1.0 and 1.5 s. When the target appeared, the participant had to move the cursor quickly and accurately from the centre onto the target. The subjects were instructed to fixate the centre of the display during the centre-hold and until the end of the trial

location(s) at which the target might appear. The target was a white disc of same size as the cues and presented at the location of one of them. Cues that did not become the target remained on the screen during target presentation. When the target appeared, the participant had to move the cursor quickly and accurately from the centre onto the target. The trajectory of the cursor had to stay within a straight path that had the same width as the target; otherwise, the trial was counted as a movement direction error.

Uncertainty varied because the number of spatial cues ($N = 1$, 2, or 3), indicating where on the screen in front of the participant the target could appear, varied. Three different cue directions relative to the centre of the screen were used: 45°, 165° and 285°. All seven possible combinations of one-, two-, and three-cue locations were used. That is, there were three one-cue conditions, one for each location; three two-cue conditions, made of all possible pairs; and one three-cue condition, when all three locations were cued. Each cue in each cue combination became the target the same number of times. In the magnetoencephalography study, there were 28 trials of each cue combination with additional trials added for the three-cue condition to equalise the number of trials with 3 cues with the one- and two-cue conditions. In the psychophysics study, there were 30 trials of each cue combination without the addition of extra trials to the three-cue condition. Trials with different cue combinations were presented in a pseudorandom order.

The reaction time (RT) was defined as the time elapsed between the onset of the target and the exit of the cursor from the centre window. Trials with RT <100 ms or >1000 ms were counted as RT errors. In addition, moving the cursor before one of the cues turned into a target resulted in an error being recorded. Finally, simply 'crossing' the target with the cursor without remaining within the target area for at least a set amount of time (100 ms) also resulted in an error. When an error occurred, the trial was randomly reinserted in the list of remaining trials so that each participant had a complete set of valid trials in all conditions.

An intertrial interval of 3 s separated each trial. Participants were given a brief period of practise before the actual task began and had a short break midway through the task. The task was controlled using a (Microsoft Visual Basic) custom-made computer program.

Analysis

Data extraction was performed using custom-written MATLAB (R2009b, The MathWorks Inc., Natick Massachusetts) code. All further data analyses were performed using the statistical programming language R (R Development Core Team 2011). For analysis purposes, errors for RT <100 ms and for movement initiated after the presentation of the cues but before the presentation of the target were analysed together as 'early errors', whereas errors due to directional inaccuracy or failure to stay within the target for the minimal target-hold time were analysed together as 'precision errors'. Variables used for the analyses were as follows: BIS score (Patton et al. 1995), RT averaged per subject for each of 3 conditions corresponding to 1, 2 and 3 cues, and error ratios for early errors and precision errors for the same 3 conditions. In these error ratios, the numerator was the number of error trials (early or precision) whilst the denominator was the number of correct trials plus the number of error trials on the numerator.

Outlier analysis

The dataset was examined for the presence of outliers using the R package 'mvoutlier' (Filzmoser and Gschwandtner 2011), which allows for the robust evaluation of multivariate datasets. All the above variables were entered in that analysis, and a tolerance for solutions that would identify up to 2 outlying subjects was selected. No outlier was detected.

GLMM analysis

Subsequently, each of these variables was used as the dependent variable in a generalized linear mixed model (GLMM) analysis performed with the R package 'lme4' (Bates et al. 2012). GLMM extends the mixed linear model, where both fixed and random effects can be included, to non-normal distributions through the use of appropriate 'link' functions. Explanatory variables entered as fixed effects were gender, cue condition (1, 2 or 3 cues) and BIS score (minus its overall mean). Furthermore, in order to probe further the mechanisms underlying task performance, we performed a 'speed–accuracy' analysis where, depending on the model, 'accuracy' refers to early or precision errors. To this end, GLMM models for early and precision errors were run where the fixed effect of RT was entered along with gender and cue condition. In all GLMM models, variables entered as random effects were subject and sub-sample.

The distribution model for the GLMM analysis was selected after inspection of relevant histograms and QQplots, as well as comparison of fitted models using the Akaike information criterion. Consequently, for the early errors, the binomial distribution was selected, using the denominators of the error ratios as 'weights', whereas the normal distribution was selected for RT and precision errors.

ANOVA results for the Wald test using type III sums of squares were obtained from the fitted GLMM models using the R package 'car' (Fox and Weisberg 2011). In addition, supplementary post hoc analyses were performed for the GLMM models for early errors, which were run for subsets of the dataset to better define the effect of gender and cue condition.

GAMM analysis

Given that the simple GLMM models of RT and precision errors with impulsivity were uninformative, we explored whether a model linking all three of these variables could account for the data. For this reason, we used Generalised Additive Mixed Models (GAMMs) as implemented in the R library 'mgcv' (Wood 2011). This approach has the advantage of taking into account non-linearity in the data in a flexible manner whilst avoiding overfitting. GAMMs are extensions of the generalised linear model in which nonparametric functions of the predictor variables are estimated using penalised splines. Here, we used cubic splines. Functions of more than one variable where there is anisotropy among the variables involved due to scale and distribution differences can be modelled as scale invariant tensor product splines. Like in the GLMM analyses described above, random effects can also be incorporated in the model. We used restricted maximum likelihood (REML) to fit the model. The success and robustness of this approach were validated against fits using maximum likelihood and generalised cross-validation.

In our analysis, the GAMM model included RT and BIS score as a tensor product spline. Sub-sample and subject were entered as random effects. Cue condition was entered as a factor. The normal distribution was selected to describe the precision errors using a procedure similar to the one for the GLMMs. In essence, this analysis resulted in the fitting of 3 'performance manifolds' to explain precision errors, one for each cue condition. One can consider such performance manifolds as indicators of both the 'style' or 'strategy' used in performing the task depending on how much uncertainty there is and of the effects of impulsivity on those styles.

Results

GLMM models

Error ratios

For early error ratios, there was a significant main effect of BIS score indicating more early errors in participants with elevated impulsivity (Chisq $= 4.80$, $df = 1$, $p = 0.028$). Furthermore, there was a main effect of cue condition—fewer errors as cues increase- (Chisq $= 443.022$, $df = 2$, $p \leq 2.2\text{e}{-16}$). In addition, there was a significant cue by gender interaction (Chisq $= 6.74$, $df = 2$, $p = 0.034$) and a significant cue by gender by BIS score interaction (Chisq $= 17.45$, $df = 2$, $p = 0.00016$). Post hoc analyses confirmed a net effect where highly impulsive women tended to have more early errors in the one-cue low uncertainty condition (Chisq $= 28.84$, $df = 1$, $p = 7.8\text{e}{-08}$), whilst the same was true for men in the high uncertainty three-cue condition (Chisq $= 13.71$, $df = 1$, $p = 0.00021$).

Figure 2 shows the effects of the BIS score on early error ratios.

No significant effect was identified for the model involving the precision error ratios.

Reaction time

For the model of reaction time, there was a significant effect of cue condition—the higher the number of cues, the longer the reaction time—(Chisq $= 1{,}006.44$, $df = 2$, $p < 2.2\ \text{e}{-16}$).

Speed–accuracy

As noted above, early errors were also explored in a supplementary 'speed–accuracy' GLMM model. In that model, there was a main effect of cue condition (Chisq $= 56.51$, $df = 2$, $p = 5.3\text{e}{-13}$) and gender (Chisq $= 11.09$, $df = 1$, $p = 0.00086$) but not RT. However, all two and three-way interactions were significant (for the cue by gender by RT interaction, Chisq $= 7.77$,

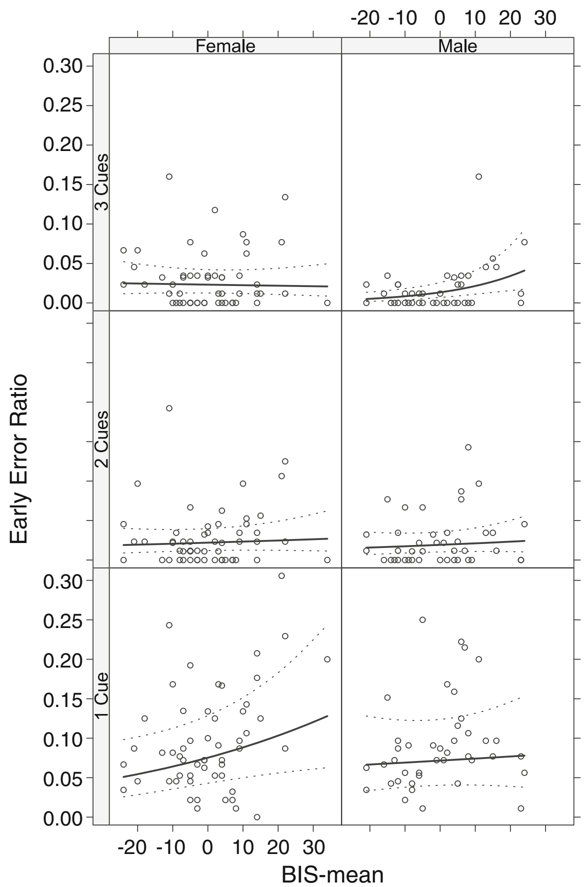

Fig. 2 Early errors versus BIS score (centred to 0 using the mean = 62) by gender and number of cues. *Each dot* in *each panel* represents the data from one subject. The *bold line* shows the fit of the GLMM model, whereas the *dotted lines* indicate the standard error

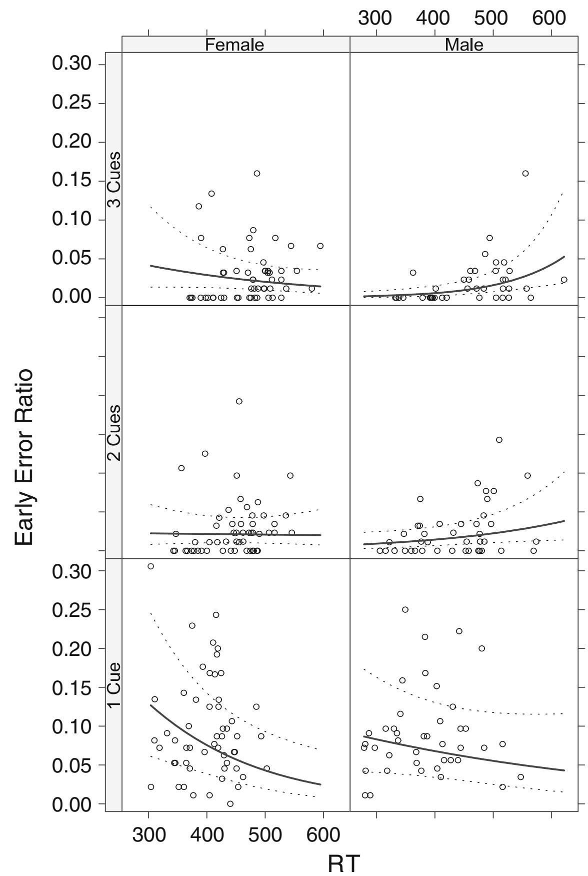

Fig. 3 Early errors versus RT (in milliseconds) by gender and number of cues. Same conventions as in Fig. 2

$df = 2$, $p = 0.020$). Post hoc tests showed the model to be significant for women in the one-cue condition ($p = 2.2e{-}11$) and the three-cue condition ($p = 0.0039$) and for men in the two- ($p = 0.0044$) and three-($p = 0.00077$) cue conditions.

Figure 3 shows the effect of RT on early error ratios per gender and number of cues. There was a significant tendency for women to have fewer early errors as RT increased, most strongly in the one-cue condition, whereas for men, the reverse was true in the two- and three-cue conditions.

No significant effect was identified for the speed–accuracy model involving the precision error ratios.

GAMM model

Figure 4 displays performance manifolds for one, two and three cues, respectively, whereas Fig. 5 displays the performance manifold for 3 cues with more detail. Based on the GAMM model evaluated, only the three-cue condition manifold was significant ($F = 2.61$, estimated $df = 7.70$, $p = 0.0058$). In conditions of high uncertainty (i.e., 3 cues), low impulsivity (as measured by BIS) was associated with frequent precision errors when RT was high, whereas high impulsivity was associated with more frequent errors when RT was comparatively low.

Discussion

In this study, we focused on the effect of impulsivity on decision-making for action by imposing a constant performance demand modulated by uncertainty about the motor action to finally adopt. There are no explicit manipulations involving speed, accuracy or reward. This contrasts with and complements past work which has focused on the effect of impulsivity on 'binary' perceptual decisions, often differentially weighted for speed, accuracy or reward. In the 'Matching Familiar Figures Test' (MFFT), high impulsives tend to adopt 'fast but error prone' strategies that may nevertheless result in similar pay-offs to low impulsives across a variety of different constraints (Dickman and Meyer 1988). A proneness to errors was also noted in a study of pathological gamblers

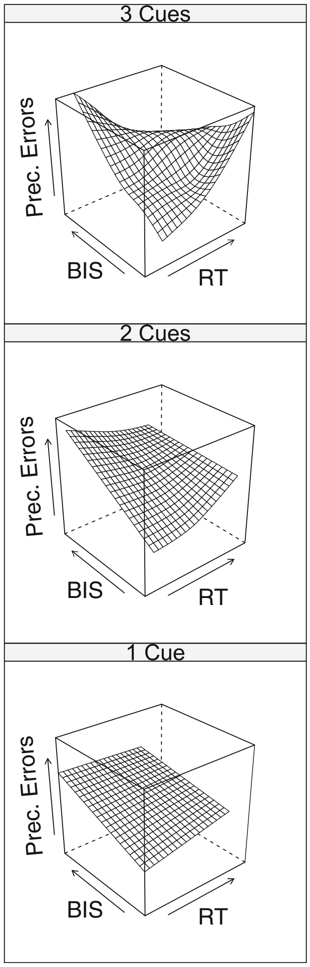

Fig. 4 Performance manifold model of ratio of precision errors against BIS score and RT for each cue condition. Axes ranges: 'Precision Errors': 0–0.23, 'BIS': 38–96, 'RT': 278.5–621.5 ms

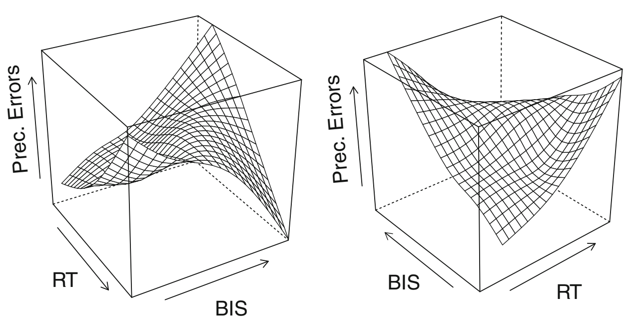

Fig. 5 Performance manifold for three-cue condition—seen from 2 perspectives for clarity

using the MFFT (Kertzman et al. 2010). Furthermore, in the 'Information Sampling Task', which involves the making of a binary choice based on self-controlled accessing (either penalised or not) of increasingly more information, high impulsives tend to sample less information for a lower probability of percent correct responses (Clark et al. 2006). Finally, in a perceptual detection task with varying degrees of reward for 'speed' or 'accuracy' sessions, the impulsivity dimension of ADHD was found to be responsible for a 'poorer speed versus accuracy trade-off' (Mulder et al. 2010). In the current study too, high impulsivity is linked to a proneness for commission errors that is modulated by both uncertainty and gender. In addition, we found that high uncertainty seems to favour different response modes for high versus low impulsives for virtually equivalent precision performance. This reaffirms and extends the characterisation of impulsivity as a 'dimension of style rather than ability' (Dickman and Meyer 1988).

Early errors: These were successfully and parsimoniously modelled with a GLMM, making a more complex approach (i.e., GAMM) redundant. Early errors increased with BIS score, but this effect was modulated by uncertainty and gender. Indeed, for women, the effect was significant in the one-cue condition—where most of the early errors occurred overall—whilst for men, there was a small but significant analogous effect in the high uncertainty three-cue condition. This increase in 'errors of commission' for individuals with elevated impulsivity has been widely reported in other sensory motor tasks including 'go/no-go' and continuous performance tasks (Dougherty et al. 2000; Keilp et al. 2005). Indeed, the count for errors of commission is often used as a proxy measure of impulsivity (Dougherty et al. 2000). The one-cue condition of the task used here is similar to those tasks, and the lack of effect for men here replicates results from past studies with male-only participants where the BIS scale has been used (Horn et al. 2003; Lane et al. 2003). In fact, gender differences may well be partly responsible for conflicting results seen in the literature (Gay et al. 2008). On the other hand, the effect seen for men in the high uncertainty condition is novel and in tune with studies pointing to gender-specific mechanisms involved in the inhibition of prepotent responses.(Yuan et al. 2008; Liu et al. 2012). In order to explore a potential speed–accuracy trade-off dependent on uncertainty, we analysed the relation of early errors and RT in a GLMM. This analysis showed a significant speed–accuracy trade-off for women, as has been shown in past studies (Rentrop et al. 2008), but a reverse effect for men and only for higher uncertainty conditions.

Precision errors and performance manifolds: There was no difference in precision errors for different levels of impulsivity and uncertainty, nor was there a speed–accuracy trade-off for precision errors. In this task, precision required successful planning of both trajectory and end-point deceleration. The lack of effect of trait impulsivity on precision performance can thus be considered indicative of impulsivity affecting less the process of planning and performing a selected course of action and more the process of action selection itself (as evidenced by the early error effects). However, as became clear through the fitting of performance manifolds, this is despite and indeed because of the adoption of different response styles by high versus low impulsives for increasing degrees of uncertainty. Indeed, the shape of the performance manifold in the three-cue condition suggests that for high impulsives optimal performance (i.e., minimal precision errors) at high uncertainty was linked to relatively higher RT, whereas for low impulsives, optimal performance was linked to relatively lower RT.

Past work on the task used here (Pellizzer and Hedges 2003) suggested a ‘shared capacity’ model of processing in which different possible actions represented by the different cues are concurrently represented until the target is displayed. This invokes the idea of a flexible but finite ‘computational capital’ that is taxed more and more as the number of cues and hence uncertainty about an upcoming movement increases. In addition, we have previously shown in a magnetoencephalography study (Tzagarakis et al. 2010) that beta-band desynchronisation over the motor cortex scales with response uncertainty and increasing RT, suggesting that uncertainty modulates movement planning in the motor cortex. In principle, the effects of high vs low trait impulsivity on task behaviour could be attributed either to differences in the size of the shared capital mentioned above or to differences in the way (including the stability) with which different options are represented in it. The similar RT performance for different BIS scores would seem to rule out a difference in the size of the computational capital, as a smaller capital should lead to longer RT, especially as the number of cues increases. On the other hand, early errors were more numerous for high impulsives and, as our analysis of early errors versus RT showed, in the case of women, this comes in the context of a speed–accuracy trade-off. This is compatible with highly impulsive women being able to commit resources more rapidly in preparing for concrete action but also being less able to adapt their planning in order to accommodate timing and/or required changes in motor plans. This may mean that motor cortex gating is compromised in a particular way in such situations, perhaps through beta-band levels that are consistently closer to the action threshold. For impulsive men, gating may be affected differently. The fact that they were disadvantaged (i.e., relatively more early errors) in the high (3 cues) rather than the low uncertainty condition pleads against a consistently low gating threshold. Also, as uncertainty increased, they tended to make fewer early errors with shorter RTs, that is, there was a reverse speed–accuracy trade-off. In this case, high uncertainty may mean more instability in the representation of alternative movement plans as well as occasions where an inordinately large weight is given to one of the options available. The latter effect is the likelier of the two given that there was a reverse speed–accuracy trade-off for early errors. Indeed, a globally ‘noisy’ representation of alternatives should not produce a consistent speed–accuracy relationship, whereas taking a ‘bet’ on one of the options is likely to result in more early errors for that specific option whereas falling back on the remaining two options would result in an increase in RT. Either process would in the end lead to the commission of the small but non-negligible number of early errors observed in men when uncertainty is high. This divergence in mechanisms linked to gender would still allow for the shared tendency for longer RT in high uncertainty conditions seen for high impulsives in the three-cue performance manifold as for women motor gating may tend to overcompensate for the low gating threshold in the low uncertainty condition whilst for men, noisier motor selection or switching to a new motor plan from an excessively weighted alternate, would both incur a penalty in RT.

The variability of context-dependent effects of impulsivity highlights the need for further study of the interaction of impulsivity and environment both in health but also—crucially—in disease. Indeed, based on the above, in a mental health setting, where impulsivity can be at the source of much morbidity, one would want to minimise its potentially deleterious effects whilst at the same time leveraging the fact that it can be responsible for varied and sometimes useful approaches in responding to a wide range of circumstances. Optimal pharmacological and psychological strategies should take into account both factors as well as the potential for gender differences in how impulsivity affects behaviour. For example, one focus of psychological approaches might be ‘cognitively untrapping’ highly impulsive patients from the impression that they only have limited-binary options in dealing with a difficult situation—this seems particularly important in women. Indeed, an impulsive suicidal patient may tend to cognitively limit her decision-making to acting upon her suicidal thoughts versus not acting, which imposes a heavy behavioural inhibition burden, whilst being shown that her option range is far wider may make it easier to abstain from toxic behaviour. This may indeed be at the source of the success of ‘distraction’ techniques employed by mental health workers in the field when counselling patients in crisis. Furthermore, it may be possible to use psychotherapeutic techniques such as mindfulness (Keng et al. 2011) to ‘balance’ the decision-making process when high uncertainty prevails. Similarly, in psychopharmacology, effective assessment of the influence of pharmacological agents on impulsivity should involve not only testing the ‘no-go error’ profile in both genders, but also testing a beneficial (or at least non-detrimental) drug effect on precision-related performance parameters, especially in conditions of higher uncertainty.

In conclusion, this study provides evidence that impulsivity measured through self-report modulates response styles in action decisions depending on the degree of uncertainty concerning the action to be performed. This effect is further modulated by gender in that there is a different pattern of early errors in men and women with the latter being burdened by early errors and a speed–accuracy trade-off in low uncertainty whilst the former have an early error burden in high uncertainty with accompanying reverse speed–accuracy trade-off. In addition, high uncertainty seems to induce distinct response styles for high and low impulsives, with optimal performance being associated with different RT profiles for the 2 groups. We believe that these findings should inform further research on the interaction of environment and trait impulsivity as well as attempts to better understand the role of impulsivity in clinical settings.

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