Bayes, Time Perception, and Relativity: The Central Role of Hopelessness

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Abstract

Time judgement and time experience are distinct elements of time perception. It is known that time experience tends to be slow, or dilated, when depressed, but there is less certainty or clarity concerning how depression affects time judgement. Here, we use a Bayesian Prediction Error Minimisation (PEM) framework called 'distrusting the present' as an explanatory and predictive model of both aspects of time perception. An interval production task was designed to probe and modulate the relationship between time perception and depression. Results showed that hopelessness, a symptom of severe depression, was associated with the ordering of interval lengths, reduced overall error, and dilated time experience. We propose that 'distrusting the future' is accompanied by 'trusting the present', leading to the experiences of time dilation when depressed or hopeless. Evidence was also found to support a relative difference model of how hopelessness dilates, and arousal accelerates, the rate of experienced time.

Keywords: time perception, time experience, Bayesian inference, prediction error minimisation, hopelessness, relativity, autonomic arousal

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1. Introduction

Many factors can cause the subjective experience of time to speed up (accelerate) or slow down (dilate). Long empty intervals are associated with dilated time experience (Droit-Volet et al., 2017), as are delayed stimulus onset (Loftus, Schooler, Boone, & Kline, 1987; Osuna, 1985) and sub-optimal processing loads associated with boredom (Zakay, 2014). Thönes and Oberfeld's (2015) meta-analysis showed that depressed people tend to experience time dilation. However, and perhaps in a manner similar to boredom, Tipples (2018) found that time dilation is predicted by feelings of frustration more than it is by feelings of sadness.

At the opposite extreme, the experience of time is accelerated in situations where cognitive processing is optimal and perceived delays are minimal (i.e., the opposite of boredom) in what is commonly called a 'flow state' (Csikszentmihalyi, 1975). Similarly, people in a manic state of hyperarousal also tend to experience time as accelerated (Bschor et al., 2004; Mezey & Knight, 1965; Moskalewicz & Schwartz, 2018). Many studies and theoretical models have demonstrated that arousal is a key accelerant of time experience (Gil & Droit-Volet, 2012), but attention to time is also a critical factor (Burle & Casini, 2001; Glicksohn, 2001).

According to the most longstanding and widely cited models of time perception, commonly referred to as the 'internal clock', timing begins with a 'clock' stage that is itself broken into discrete stages relating to arousal and attention (Treisman, 1963). Arousal is theoretically related to the 'pacemaker' which sets the tempo of the clock, whereas attention is related to the 'switch' or 'gate' that sends timing signals to an 'accumulator' (Allman, Teki, Griffiths, & Meck, 2014; Burle & Casini, 2001). More specifically, arousal speeds up the internal pacemaker (Gil & Droit-Volet, 2012; Zakay & Block, 1997) and attention to time directs temporal information to the accumulator (Zakay & Block, 1995; Zakay & Block, 1996). Timing judgements are then made on the basis of this temporal information stored in the accumulator.

According to Glicksohn's (2001) interpretation, higher levels of arousal and/or attention focused on the *task* leads to the rapid accumulation of small units of time (i.e., acceleration), whereas lower levels of arousal and/or more attention paid to *time* leads to the slower accumulation of larger time units (i.e., dilation). An example of this distinction is that, although in a low arousal state which might otherwise lead to a slow accumulation/passage of time, mindfulness meditators can be so immersed in the mindfulness task that they pay virtually no attention to time and so time experience is accelerated (Droit-Volet, Chaulet, & Dambrun, 2018).

When engaging such models of time perception in the context of depression, it is important to stress the distinction between time experience and time judgement. A recent meta-analysis by Thönes and Oberfeld (2015) showed that depressed patients tend to report their *experience* of time as slowed. As noted by Thönes and Oberfeld (2015), time experience is typically measured using a visual analogue scale (VAS) from 'very fast' to 'very slow' where, unlike time judgement tasks, "the concept of interval duration does not apply" (p. 364). This is in contrast to time *judgement* tasks which must occur over an interval (or range of intervals) of a given duration (Droit-Volet & Wearden, 2016). To reinforce this distinction, the same meta-analytic study showed that depressed patients' performance on time judgements tasks is not uniformly slow, late or under/over-estimated compared to controls (Thönes &

Oberfeld, 2015). The situation is thus more complex for time judgement than for time experience in depression and requires further study.

The divergence between findings of time experience and time judgement in depression may stem from the fact that previous approaches mainly deal with early ‘clock’ stages of information processing. A comprehensive model of time judgement must also include ‘memory’ and ‘decision’ stages. One of the main aims of the present paper is to explain the apparent mismatch in depression between time experience and time judgement in terms of a Bayesian model of time perception, focused on the notion of ‘distrusting the present’ (Hohwy, Paton, & Palmer, 2016). This model proposes that perceived time speeds up or slows down depending on how inferences are made on the basis of memory and sensory data.

1.1 Prediction Error Minimisation and Time Perception: ‘Distrusting the Present’

Bayesian Prediction Error Minimisation treats the brain as a sophisticated hypothesis-testing machine that attempts to make accurate predictions (of the future) based on limited information available in (present) sensation and (past) memory (Clark, 2015; Friston, 2010; Hohwy, 2013). Bayesian statistics operationalise these concepts by describing how the brain seeks to minimise error (i.e., the value of the loss function) of predictive inference (i.e., the posterior distribution) by selectively weighting probabilities based on prior experience (i.e., the prior distribution) and present sensory data (i.e., the sensory likelihood distribution) (Mathys et al., 2014; Palmer, Lawson, & Hohwy, 2017). Shi, Church, and Meck (2013) mapped these distributions onto information processing stages of interval timing as per the dominant internal clock model above: 1) the sensory likelihood distribution equates to the 'clock' stage that modulates tempo and duration via a pacemaker, switch, and accumulator; 2) the posterior and prior distributions equate to the working and reference memory aspects of the 'memory' stage; and 3) the loss function equates to the 'decision' stage. Kent (2018) has also mapped these functions onto the three major brain networks (i.e., salience, default mode, and central executive).

The 'decision' stage of interval timing reflects the core Bayesian function of making predictive inferences to determine the causes of sensory input. Hohwy et al. (2016) developed a PEM account of time experience focused on the notion of *distrusting the present* where the rate of flow of experienced time varies depending on how quickly a (Bayesian) observer 'decides' that the *present* predictive inference (h_0) is less trustworthy than the next inference (h_1), where trust is operationalised as the relative precision of h_0 and h_1. The more quickly one becomes certain (i.e., decides) that h_0 has optimally predicted present sensory data, the more quickly h_1 is required to explain incoming sensory data. More rapid passage through successive inferences leads to more rapid passage of time.

So, in order to endorse h_1 over h_0, and thus experience temporal flow, expectations about the predictability or reliability of the future are acutely relevant. Each decision must be made by weighting the limited ability to infer present causes against the likely ability to predict future causes. To connect this account to time perception in depression, we accordingly reason here that hope for the future is critical within a PEM framework requiring people to 'distrust the present' because, in doing so, they must simultaneously 'trust the future' in a hopeful way. Hopefulness represents a degree of certainty about future PEM, a tendency to endorse h_1, and an accelerated experience of time.

1.2 Prediction Error Minimisation of Time Perception in Depression: 'Distrusting the Future'

Given the Bayesian approach, hopelessness (i.e., 'distrusting the future') should be correlated with a tendency to 'trust' h_0 over h_1, and thus experience time more slowly. Hopelessness is one of the major symptoms of depression, especially severe depression, and is closely related to future time perspective (Beck, Weissman, Lester, & Trexler, 1974). If there is a common basis for time dilation experienced during long empty intervals (Droit-Volet et al, 2017), boredom (Zakay, 2014), frustration (Tipples, 2018), and depression (Thönes & Oberfeld, 2015), such that they are all due to increased attention paid to time (Glicksohn, 2001), then it is possible that long, empty intervals that induce boredom may also cue a state of hopelessness. A longer second interval compared to the first, for example, could prompt people to feel they are 'waiting' a *relatively* long time for the second interval to end and so feel somewhat bored or frustrated. This effect could enhance attention paid to time (Glicksohn, 2001), have a deleterious effect on the decision stage of information processing (Shi et al., 2013), slow time experience (Droit-Volet et al., 2017), and increase perceived hopelessness.

It is proposed that the precise mechanism for cuing hopelessness stems from 'temporal uncertainty'. Uncertainty in the sensory environment inhibits the ability to make accurate predictions and, in terms of Bayesian time judgement, Jazayeri and Shadlen (2010) showed that relatively long intervals are intrinsically more uncertain than shorter intervals due to scalar variability. According to 'distrusting the present', and in accordance with recent findings (Droit-Volet et al., 2017), uncertainty during longer intervals could slow down the passage of experienced time and increase hopelessness. Here, ‘distrusting the future’ (h_1) slows the process of ‘distrusting the present’ (h_0) (Hohwy et al., 2016).

1.3 Modelling and Assessing ‘Distrusting the Present’

A predictive model of ‘distrusting the present’ is required to test the theory. So far, none have been proposed and so a predictive model can only be speculated on reasonable *prima facie* grounds. Any model must capture two complementary aspects: 1) the more h_0 is “trusted”, the slower time is experienced; and 2) the more h_1 is “trusted”, the more quickly time is experienced. There is, therefore, a tension between h_0 and h_1 that, at a fundamental level, can either be expressed in terms of absolute (h_0 minus h_1) or relative (a ratio of h_0 to h_1) difference. Glicksohn (2001) postulated a multiplicative model of apparent duration for two complementary aspects (size and number of time units), and so the inverse of multiplication (i.e., division or ratio) is perhaps more likely than the inverse of an additive function (i.e., subtraction).

Further reasons also suggest a relative difference model of time experience may be preferable to absolute difference. According to Glicksohn’s (2001) multiplicative model, psychological time has two polar limits: 1) accelerated timelessness associated with hyperarousal and/or highly-focussed attention where time units are so small and/or accumulate so quickly that they can no longer be perceived (as in a mindfulness/flow state or mania); and 2) dilation timelessness associated with hyper-attention to time and/or ultra-low arousal where time units become so large and/or accumulate so slowly that time no longer ‘passes’ (as in boredom or depression). These opposing poles then reflect a universal property of time. It is interesting to observe that in physics, relativity theory proposes two analogous temporal limits: 1) accelerated timelessness associated with massless particles (i.e., photons) where time and space are contracted to a point due to the particle moving at the speed of light; and 2) dilated timelessness associated with supermassive bodies (i.e., black holes) where time and space are infinitely expanded due to the warping effect of gravity (Einstein, 1920; Misner, Thorne, & Wheeler, 1973).

Given the lack of clear precedent in the literature to model 'distrusting the present', we believe it is reasonable to appeal to properties of physical time and thus model psychological time by relativity and relative difference. Although aspects of psychological and physical accounts of time thus coincide in principle, the relativistic properties of physical time might initially seem irrelevant to psychological time. However, Buhusi and Meck (2009) have shown that a meaningful analogy can be drawn between relativity theory and time judgement. Their explanation analogises the 'special' theory of relativity and hinges on the concurrent timing of multiple 'internal clocks'. Their analogy cannot apply to 'distrusting the present' because, as explained above, time experience is not defined according to clock-based interval durations. Instead the 'general' theory of relativity, which describes time dilation under gravity, may be more fit for the current purpose (Einstein, 1920). To illustrate, time dilation due to gravity can be calculated according to a relative difference equation in a simplified form of the Schwarzschild metric (Schwarzschild, 1916), below:

$$Time\ dilation \approx \sqrt{1 - \frac{mass}{distance}} \tag{1}$$

The two variables, mass and distance (or gravitational potential energy) represent the two physical temporal limits described above. From the equation it follows that: 1) infinite time dilation occurs (i.e., time stops) when mass (which can itself be measured as a distance, the Schwarzschild radius of a black hole, r_s) equals or exceeds the distance to that mass (i.e., the square-root of 0 is undefined); and 2) infinite time acceleration occurs (i.e., time passes imperceptibly fast) when mass is zero or distance/energy is infinite, as in the case of a massless photon.

As above, these are analogous to the two temporal limits described by Glicksohn (2001) and can be substituted as:

$$Time\ dilation\ \approx \sqrt{1 - \frac{size\ of\ time\ units}{number\ of\ time\ units}} \tag{2}$$

Given no standard units are available to measure 'size' or 'number' in Equation 2, proxy measures proposed by Glicksohn (2001) are used instead:

$$Time\ dilation\ \approx \sqrt{1 - \frac{attention\ to\ time}{arousal}} \tag{3}$$

In terms of 'distrusting the present' and the current experimental design, where attention to time is operationalised as hopelessness, the equation takes the form:

$$Time\ dilation\ \approx \sqrt{1 - \frac{hopelessness}{arousal}} \tag{4}$$

These proxy measures are therefore taken to represent the degree to which weighting is given to either h_0 via hopelessness or h_1 via arousal.

$$Time\ dilation \approx \sqrt{1 - \frac{h_0}{h_1}} \quad (5)$$

An added advantage of preferring the relative difference equation is that relative difference is also a feature of a Bayesian loss function which Shi et al. (2013) associated with the ‘decision’ stage of interval timing:

$$Error = \left(1 - \frac{Estimated\ interval}{Target\ interval}\right)^2 \quad (6)$$

This relative squared-error loss function (involving a ratio in Equation 6) is preferable to absolute squared-error (i.e., target interval minus the estimated interval, squared) because the amount of error is scale or interval invariant (Sun, Wang, Goyal, & Varshney, 2012). This means that error in the estimate is effectively a (relative) proportion of the target interval in question. Scale invariance, in turn, allows Bayesian accounts of time perception to accord with preceding models related to scalar expectancy theory (Gibbon, 1977; Shi, Church, & Meck, 2013).

A critical feature of PEM and ‘distrusting the present’ is that error minimisation, given its association with the ‘decision’ stage of timing and the loss function, can be quantified in relation to this relative squared-error on a series of time judgement tasks. This suggests that the ‘decision’ stage of internal timing is optimised so that a lower *overall* error is achieved at the expense of error in any one particular judgement. A common way this is achieved in time perception is through the central tendency effect (Treisman, 1963), whereby individuals bias judgements towards the (moving) average of intervals presented. In a Bayesian context, this averaging is done in order to deal with uncertainty in a noisy or volatile sensory environment (Jazayeri

& Shadlen, 2010; Karaminis et al., 2016). In time judgement tasks, this central tendency leads to a so-called Vierordt effect such that shorter intervals are judged as 'longer' than they really are, and longer intervals are judged as 'shorter' than they really are (Lejeune & Wearden, 2009). It is expected that increased hopelessness, in a manner similar to a depressive realism effect (Kornbrot, Msetfi, & Grimwood, 2013; Moore & Fresco, 2012) and enhanced error detection in depression (Chiu & Deldin, 2007), should be associated with low *overall* error on an time judgement task (i.e., judgements by those higher in hopelessness should be closer to veridical *on average* compared to those lower in hopelessness).

Although there are a multitude of ways to assess time judgement, and different methods produce seemingly contradictory results, here we focused exclusively on interval production tasks. We have done so because they are particularly sensitive to whether attention is being paid to time or some other concurrent task (Zakay & Shub, 1998). Production methods require individuals to manually judge duration by indicating the start and/or end of a target interval, which is different to verbally estimating an interval (i.e., passively judging interval length in seconds or minutes), or even reproducing an interval that has been presented previously.

1.4 Aims and Hypotheses

There are separate literatures showing that symptoms of anxiety (i.e., arousal) speed up, while symptoms of depression (i.e., hopelessness) slow down, the rate of perceived time (Gil & Droit-Volet, 2012; Thönes & Oberfeld, 2015). They have not been viewed in tandem and we believe the literature will be extended by simultaneously accounting for factors that dilate and contract perceived time. An experiment involving a time production task and self-reported time experience was set up to test the above Bayesian PEM model of time perception (i.e., both experience and judgement) in relation to hopelessness and arousal. Based on previous research, it was expected that: (a) hopelessness would correlate with reduced relative squared-error of interval production; (b) hopelessness would be associated with longer second than first intervals; (c) hopelessness would be associated with slow time experience, while autonomic arousal would be associated with fast time experience; and (d) a proxy model of a square-rooted relative difference equation involving hopelessness and arousal, as above, would explain more variance in time experience than an absolute difference between hopelessness and arousal.

2. Method

2.1 Participants

The sample comprised 64 people (38 females) ranging from 17 to 55 years of age (*M* = 35.00 years, *SD* = 6.94). Missing data were replaced using multiple imputation for two participants' time production data, two participants' breathing rate data, and six participants' hopelessness scores.

Participants were screened for depression symptoms (Patient Health Questionnaire 9-item, PHQ-9), anxiety symptoms (Generalised Anxiety Disorder 7-item, GAD-7), insomnia (Insomnia Severity Index, ISI), alcohol and illicit drug use (Cut-down, Annoyed, Guilty, and Eye-opener Alcohol Illicit Drug, CAGE-AID), and cognitive processing speed (Trail Making Test, Part A). According to pre-test psychometric screening tools, none of the participants experienced severe anxiety

(GAD-7 max = 13, *M* = 2.83, *SD* = 2.75), depression (PHQ-9 max = 16, *M* = 3.19, *SD* = 3.15), insomnia (ISI max = 13, *M* = 3.94, *SD* = 3.46), or slow cognitive processing (Trail Making Test A max = 35 s, *M* = 21.91 s, *SD* = 4.76 s) (Bastien, Vallières, & Morin, 2001; Kroenke, Spitzer, & Williams, 2001; Reitan, 1958; Spitzer, Kroenke, Williams, & Löwe, 2006). Heart rate variability (HRV) 25/50/75 interquartile statistics were all within normal ranges (SDNN = 34/58/75, LF:HF = 1.2/1.8/2.2) (Shaffer & Ginsberg, 2017). No outliers were removed.

2.2 Materials

In order to allow for later comparison with clinical samples, several clinical screening tests were used on the current sample of healthy volunteers. The ISI assesses sleep disturbance across seven items (e.g., “How WORRIED/DISTRESSED are you about your current sleep problem?”) on five-point Likert scale (Bastien, Vallières, & Morin, 2001). The Trail Making Test Part A assesses cognitive processing speed by asking participants to link a spatially distributed series of numbers as quickly as possible while making as few errors as possible (Reitan, 1958). The CAGE-AID screens for problematic alcohol and illicit drug use with four yes/no items relating to different aspects of dependence and misuse (Bush, Shaw, Cleary, Delbanco, & Aronson, 1987). The PHQ-9 and GAD-7 screen for depression and anxiety symptoms, respectively, over the previous two-week period (i.e., “Over the past two weeks, how often have you been bothered by the following problems?”) asking people to report the frequency of certain behaviours or experiences (e.g., “Little interest or pleasure in doing things” or “Feeling anxious, nervous or on edge”). Both scales are rated on four-point Likert scales of frequency (i.e., “Not at all”, "Several days", "More than half the days", and "Nearly every day"; Kroenke, Spitzer, & Williams, 2001; Spitzer, Kroenke, Williams, & Löwe, 2006). The 20-item Beck Hopelessness Scale (BHS) assesses levels of hopelessness over the preceding week (i.e., states) using true/false responses to items relating to feelings about the future, loss of motivation, and expectations (Beck et al., 1974).

2.3 Procedure

In line with Human Research Ethics Committee clearance (A15-105) from Federation University, participants read a plain language statement and provided written consent prior to participation. No reimbursement was offered for participation. Exclusion criteria included insomnia, drug or alcohol dependence, impaired cognitive processing speed, and visual impairment. One participant was excluded on this basis. Electronic materials were displayed on a 21" Apple iMac (2011) or 13" MacBook Pro (2013) via an internet browser (Safari, Chrome, or Firefox). Participation took place in a quiet, distraction-free environment between 9am and 9pm. Participation took between 30 and 45 mins in total.

In order to measure aspects of autonomic arousal, participants' HRV indices were measured first. Heart rate variability data were collected from participants using a Polar H7 heartrate monitor and "HRV logger" iOS application on an iPhone 5s. Participants laid supine in a quiet room for 10 mins and were instructed to breathe normally, minimise movement, and to not talk. Demographics were then collected and screening tests performed. Time perception measures were then administered, and participants completed their involvement by filling out an online version of the BHS.

In the time perception tasks, participants first indicated how quickly or slowly they had experienced time on the day of the experiment on a 100 mm VAS displaying "very slow" at the bottom and "very fast" at the top. Averaging time experience over long timeframes is typical when probing the relationship to depression (Bschor et al., 2004; Mundt, Richter, van Hees, & Stumpf, 1998; Oberfeld, Thönes, Palayoor, & Hecht, 2014) and the basis for comparison in the Thönes and Oberfeld (2015) meta-analysis. Participants were then instructed to produce six randomised intervals (i.e., 10, 20, 30, 40, 60 and 90 s) by clicking "start" and "stop" icons on their screen. Participants were advised that counting was allowed. In order to ensure that the first interval production was not biased by any previous intervals (see Lejuene & Wearden, 2009), no practice intervals were offered.

Much of the experiment was modelled on Bschor et al. (2004) who used a VAS of participants' experience of time on the day of the experiment, and allowed participants to count in time estimation/reproduction/production tasks. Bschor et al. (2004) showed that depressed and manic individuals had opposite time experience (i.e., depressed = slow, manic = fast) and, for reasons addressed in the Introduction, a replication of this finding was sought in relation to autonomic/anxious arousal and hopelessness. Bschor et al. (2004) also used productions intervals over a similar range (7 – 90 s). Such ranges are common when investigating effects of depression using production tasks (Thönes & Oberfeld, 2015) and were required here to cue feelings of boredom. As shown by Danckert and Allman (2005), error associated with boredom proneness only becomes salient for intervals around 60 s duration, while Droit-Volet et al. (2017) showed that slowed time experience only becomes salient for intervals great than 33 s. Other studies using production intervals have also employed intervals beyond 10 s (Baldauf et al., 2009) and as high as 90 s (Labelle, Graf, Grondin, & Gagne-Roy, 2009).

2.4 Statistical analyses

2.4.1 Anxious and autonomic arousal.

As above, a proxy measure of the endorsement of h_1 was sought as an index of anxious and/or autonomic arousal. In line with previous research (Beard & Björgvinsson, 2014; Kertz, Bigda-Peyton, & Bjorgvinsson, 2013), a subscale of the GAD-7 questionnaire relating to anxious arousal was calculated by summing items 4-6 only. For autonomic arousal, several HRV statistics are reportable from the "HRV logger" iOS software, including average heartrate and a spectral power analysis in the high frequency (HF; 0.15-0.40 Hz) and low frequency (LF; 0.04-0.15 Hz) bands. The HRV logger also provides a ratio of the latter power bands (LF:HF) which, while an unreliable indicator or sympatho-vagal balance in the autonomic nervous system (Billman, 2013), has been correlated with spontaneous breathing rate in controlled conditions (Brown, Beightol, Koh, & Eckberg, 1993; Raghuraj, Ramakrishnan, Nagendra, & Telles, 1998; Saboul, Pialoux, & Hautier, 2014). Breathing rate and the arousal subscale of the GAD-7 were interpreted to represent anxious and autonomic facets of arousal.

2.4.2 Absolute and relative difference models of time experience.

As above, the relative difference model of time experience was calculated by standardising and transforming hopelessness and autonomic/anxious arousal scores. The absolute difference model simply subtracted the standardised and transformed hopelessness score from the standardised and transformed autonomic arousal score. The two models treat relative values of hopelessness and arousal differently. For example, when the arousal value is 1.618 and the hopelessness value is 1, then the absolute and relative difference models give the same answer (i.e., .618) and predict the same rate of time experience. However, if the hopelessness value is 1 and arousal value is less than 1.618, then the relative difference model calculates faster time experience (i.e., 0.58) than the absolute difference model (i.e., 0.50). On the other hand, for arousal values greater than 1.618 compared to a hopelessness value of 1, the relative difference model predicts slower time experience (i.e., 0.64) than the absolute difference model (i.e., 0.70). As shown in Figure 1 the relative difference function is curved and time experience decelerates more quickly as hopelessness increases compared to the absolute difference model. This is true regardless of the absolute level of arousal or hopelessness, as shown between Figure 1a and 1b, and it is only the point of equivalence that changes for different absolute values.

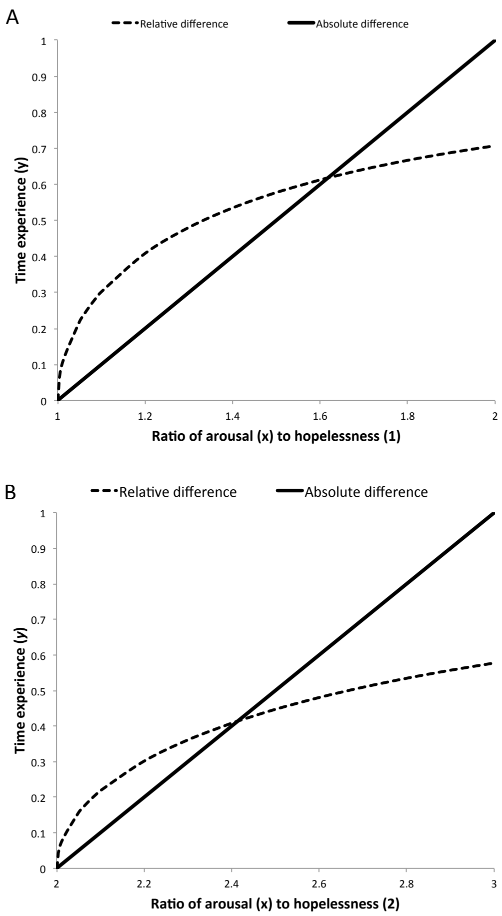

Figure 1. Illustration of different predictions of time experience (*y* axis) by absolute and relative difference models depending on the ratio of arousal (*x* axis) to hopelessness (A = 1, B = 2).

2.4.3 Bayesian and frequentist statistics.

Zero-order and partial Pearson correlations were used to demonstrate associations between variables such as hopelessness, time experience, relative squared error and autonomic arousal. The statistical control of the length of the first interval/production (i.e., inclusion as a predictor) is required due to our expectation that longer second intervals would cue boredom-like effects and subsequently affect hopelessness. Results regarding the relation of hopelessness to the relative length of the first and second intervals supported this statistical control.

In order to compare the relative difference and absolute difference models in a small sample with small-to-medium expected effect sizes (Thönes & Oberfeld, 2016), Bayes Factor multiple regression analysis was better suited to the current study. As opposed to a confidence or significance level regarding the alternate hypothesis, Bayes Factors weigh evidence for different models by quantifying how much more likely one particular model is compared to others, including the null hypothesis (Dienes, 2011; Van Doorn, Paton, Howell, & Hohwy, 2015). A Bayes Factor of $BF_{10} = 10$, for example, indicates that the model under consideration is ten times more likely than the null. Using a system devised by Jeffreys (1998), $BF_{10} > 10$ is interpreted as strong evidence for the model in question, and $BF_{10} > 100$ is interpreted as decisive evidence. Standard frequentist linear regressions were then computed to determine the strength and direction of effects in models supported by Bayes Factors. Frequentist statistics were calculated using SPSS (version 25) and Bayesian statistics were calculated using JASP (version 0.8.6).

3. Results

3.1 Descriptive statistics and bivariate correlations

Descriptive statistics in Table 1 show that, despite large ranges, interval productions were highly linear (R^2, $M = .98$, $SD = .01$). Error, time experience, breathing rate, anxious arousal and hopelessness were also within acceptable ranges. Bivariate correlations in Table 2 were consistent with predictions in showing significant correlations between models of time experience (calculated from arousal and hopelessness scores) and reported time experience, as well as hopelessness and relative-squared error across all six intervals (*r* = -.34, *p* = .005). The correlation between hopelessness and error confirmed the hypothesis (a), above.

Table 1. *Ranges, means and standard deviations of time productions, linearity, relative-squared error, time experience, arousal and hopelessness.*

Variable	Min.	Max.	*M*	*SD*
10 s production (s)	5	22	11.24	3.25
20 s production (s)	10	68	23.15	9.01
30 s production (s)	20	81	34.97	11.46
40 s production (s)	21	103	47.73	15.15
60 s production (s)	37	144	73.11	21.76
90 s production (s)	58	207	110.84	31.75
Linearity (R^2)	0.92	1	0.98	0.02
Relative-squared error	0.01	3.05	0.45	0.57
Time experience (VAS 0 - 1000)	248	949	644.97	180.32
Breathing rate (LF:HF)	.40	3.37	1.71	.63
Anxious arousal	0	6.00	1.25	1.35
Arousal (standardised)	-1.78	3.42	0.00	1.00
Hopelessness (BHS raw score)	0	8	2.26	1.75

Table 2. *Bivariate correlations between variables associated with time experience, time judgement, hopelessness and arousal.*

Variable	1	2	3	4	5	6	7	8
1. Dilation	-	-.08	-.06	-.20	.39**	.40**	-.10	.31*
2. Length of first production		-	-.78**	-.27*	.36**	.30*	.19	.19
3. Longer second interval than first			-	.32**	-.40**	-.37**	.01	-.18
4. Hopelessness				-	-.78**	-.71**	-.34**	.15
5. Relative Difference Model					-	.93**	.32**	.44**
6. Absolute Difference Model						-	.32**	.54**
7. Relative-square error							-	.04
8. Arousal								-

*$p < .05$
**$p < .01$

3.2 Hopelessness and Longer Second Intervals

Hopelessness was also correlated with random allocation to a longer second than first production interval ($r = .32$, $p = .008$), but not to subsequent interval differences (p's > .05). This confirmed hypothesis (b), above. It is also therefore necessary to control for the length of the first interval in subsequent analyses involving hopelessness. When controlling for the length of the first interval, a partial correlation between hopelessness and relative squared error remains significant, and of the same magnitude ($r = -.34$, $p = .005$). This reactive increase in hopelessness was also associated with a Vierordt central tendency effect that biased responses to a moving average of intervals presented (Shi et al., 2013) (see Appendix A for full discussion). Overall, the hypothesised associations between hopelessness, lengthening between first and second intervals, and low error were confirmed.

3.3 Hopelessness, Autonomic Arousal, and Time Experience

The hypothesised relationship between hopelessness, arousal, and time experience also needed to correct for the length of the first interval production. When controlling for arousal and the first interval production, hopelessness was negatively correlated with time experience ($r = -.33$, $p = .008$), confirming that hopelessness is associated with dilated time experience. Conversely, when controlling for hopelessness and the first interval production, autonomic arousal was positively correlated with time experience ($r = .40$, $p = .001$), confirming that arousal is associated with accelerated time experience. These results confirm hypothesis (c), above.

3.4 Relative Versus Absolute Difference Models of 'Distrusting the Present'

It was hypothesised that the relative difference equation would effectively model the combined effects of hopelessness and autonomic arousal on time experience. To test the prediction, a relative difference model of normalised and transformed hopelessness and arousal variables (i.e., anxious arousal and breathing rate) was compared to an absolute difference model (i.e., arousal minus hopelessness).

When controlling for the first interval production, Bayesian linear regression showed more evidence in support of the relative difference model (BF_{10} = 62.25, R^2 = .21) than the absolute difference model (BF_{10} = 54.30, R^2 = .21) in predicting time experience. Frequentist regression showed that the relative difference model predicted time experience ($\beta = .49$, $p < .001$) in conjunction with the first interval production ($\beta = -.26$, $p = .03$), $R^2 = .21$, $F(2, 64) = 8.62$, $p < .001$. Assumptions of homoscedasticity (Kolmogorov-Smirnov and Shapiro-Wilk tests, $p > .05$) and multicollinearity (VIFs < 2) were not violated. These results confirm hypothesis (d) above by showing that the relative difference equation performs well as a calculus of time experience from proxy measures of h_0 and h_1 endorsement such as hopelessness and arousal, respectively. Results are summarised in Figure 2, below.

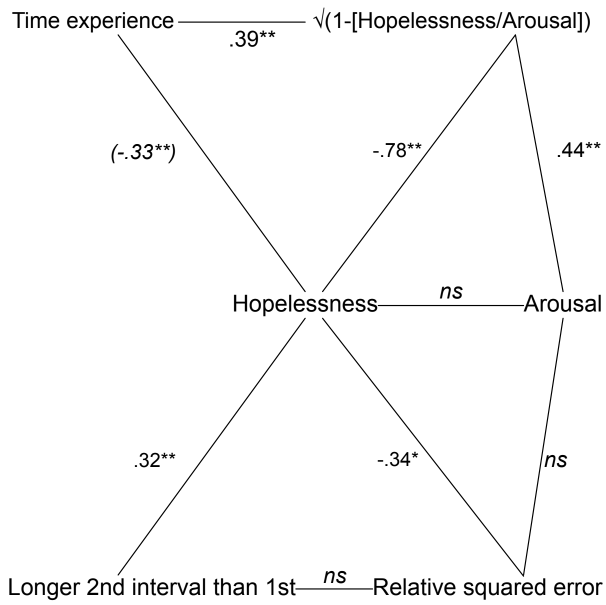

Figure 2. Hypothesised bivariate and partial (controlling for length of first interval production and arousal, italics and in brackets) correlations between hopelessness, arousal, time experience, interval ordering, relative squared error, and the relative difference model of time experience. **p* < .05, ***p* < .01

4. Discussion

Results confirmed hypothesised associations between: (a) hopelessness and low production (relative squared) error; (b) hopelessness and lengthening between first and second production intervals; (c) hopelessness with dilated, and autonomic arousal with accelerated, time experience; and (d) a relative difference equation of hopelessness and autonomic arousal as a proxy model for Hohwy et al.'s (2016) 'distrusting the present' Bayesian PEM framework of time experience. Just as arousal has been found to accelerate the 'clock' stage of interval timing and emotional time distortions (Gil & Droit-Volet, 2012; Glicksohn, 2001), hopelessness may affect the 'decision' stage of interval timing and cause cognitive time distortions such as the

Vierordt effect described in Appendix A. This experiment successfully exploited the relationship between relatively long intervals, temporal uncertainty, dilated time experience, and depressive symptomatology to demonstrate a dynamic relationship explicable within the ‘distrusting the present’ framework.

Randomised lengthening between intervals one and two may cause individuals to experience time dilation just as waiting for longer than expected causes boredom and slowed time experience (Loftus, Schooler, Boone, & Kline, 1987; Osuna, 1985). According to Zakay (2014), slowed time experience in response to boredom is a “signal which, similarly to pain, is aimed at alerting the executive system that resources should be recruited in order to cope with the hazardous state” (p. 1). In this sense, the implication for the current study is that the increased hopelessness found in response to lengthening between the first and second intervals is an index of that signal. This process is therefore thought to underpin the same phenomenon observed in severe depressive states (Thönes & Oberfeld, 2015), both in terms of dilated time experience and Vierordt-like effects of time production.

By focussing on hopelessness and showing the complex relationship between depressive symptoms and time experience, the present study provides some explanation as to why time dilation effects of depression do not, as found by Thönes and Oberfeld (2015), translate into uniformly slow judgements. In order to reduce uncertainty and overall error, a hopeless/depressed mindset may recruit a strategy of central tendency that lengthens the judgement of shorter intervals and shortens the judgement of longer intervals (i.e., a Vierordt effect). This error reduction strategy is consistent with the general framework of Bayesian PEM and ‘distrusting the present’

(Hohwy et al., 2016). The present authors have looked at this process in more detail in another paper (Kent, Klein, & Van Doorn, in preparation).

Briefly, however, the fact that hopelessness reduces overall error shows that expectations for the future affect Bayesian PEM in a systematic way. Whereas autonomic arousal and the salience network control the speed of a clock-like mechanism (Craig, 2009a; 2009b), and memory components of the central executive network calibrate the clock's function according to prior experience (Shi et al., 2013), the current study suggests that hopelessness affects the decision stage of interval timing, perhaps via the default mode network and temporal awareness (Kent, 2018; Lloyd, 2012; van Wassenhove at al., 2011). The implication for 'distrusting the present' is that hopelessness affects the loss function's role in determining the relative success or failure of the current predictive inferences, h_0.

The current study also suggests that a relative difference equation is common to psychological and physical formulations of time, common measures of time judgement error, and, as shown in Appendix A, psychophysical functions of time judgement and the Vierordt effect (Lejeune & Wearden, 2009). While it is premature to draw firm conclusions, the current study adds support to Buhusi and Meck's (2009) claim that time perception is analogous to theories of physical time (i.e., relativity theory).

4.1 Limitations of the current study

Further research is needed to address the limitations of the current study by utilising a larger sample and possibly repeating the same intervals on different occasions in order to substantiate the Bayes factor evidence for the relative difference model. A larger sample should also include symptoms of severe depression besides hopelessness (e.g., anhedonia, psychomotor retardation) to probe how they interact with Bayesian hierarchical PEM. Testing hopelessness as an independent variable prior to interval productions would also avoid the need to control for random experimental changes in hopelessness and Bayesian PEM strategies such as Vierordt effects. Direct measurement of breathing rate would also be preferable to indirect HRV measures such as the LF:HF ratio.

4.2 Conclusion

In summary, evidence has been put forward in support of an association between symptoms of depression, time perception, and Bayesian PEM using a framework called “distrusting the present” (Hohwy et al., 2016). It was shown how key variables, namely autonomic arousal and hopelessness, have a combined effect on how individuals judged and experience time. Conversely, a key variable of time perception, namely interval duration, was also shown to affect how hopeful individuals were about the future. These findings suggest new ways of interpreting the vast literature on time perception in depressive states.

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Appendix A

Supplementary Analysis of Central Tendency Effects.

It was expected that a Vierordt-like central tendency effect (Lejeune & Wearden, 2009; Shi et al., 2013) would become evident in order for individuals to reduce relative squared-error when the second interval production was longer than the first. This would be achieved by flattening the slope of production so that shorter intervals were overproduced and longer intervals were underproduced in a way similar to that reported by Thönes and Oberfeld (2015).

Linear trendlines were fitted to participants' raw productions of the second interval onwards to reveal coefficient (i.e., slope or *a*), constant (i.e., *y*-intercept or *b*), and indifference interval statistics (i.e, ii). An indifference interval is an interpolated value at which production is hypothetically neither over- or under-produced (i.e., indifferent). Whereas a flattened slope represents a central tendency or Vierordt effect, the *y*-intercept represents the constant increase or decrease averaged across productions. If you add a constant to a linear function, all points along that function are raised. In this case, a higher (positive) *y*-intercept implies that all interval productions are lengthened independent of the slope (i.e., independent of whether the productions are generally long, short or a mix of long and short). Higher intercepts represent slower or longer productions generally, and lower intercepts represent faster or shorter productions. The slope of production is calculable from *y*-intercept and indifference interval statistics according to a relative difference equation:

$$a = 1 - \frac{b}{ii} \quad (6)$$

Strong Bayesian evidence was found for a combined model predicting the slope of production for intervals two-to-six by hopelessness, age, breathing rate, and the *y*-intercept of the slope of production, BF_{10} = 136.7, R^2 = .30. Frequentist regression showed that hopelessness (β = -.29, *p* = .01), age (β = -.29, *p* = .01), breathing rate (β = -.27, *p* = .02) and *y*-intercept (β = -.36, *p* = .001) were significant predictors of the slope of production, R^2 = .30, $F(4, 66) = 6.51$, $p < .001$. Although the assumption of multicollinearity (VIFs < 2) was not violated, standardised residuals were heteroscedastic (Kolmogorov-Smirnov and Shapiro-Wilk tests, $p < .05$). However, regression results are robust to minor violations of homoscedasticity (Nimon, 2012).

The slope of production was highly correlated with mean production error between intervals two and six, *r* = .88, $p < .001$, suggesting that individuals minimised average error from interval two onwards by reducing the slope of production in the context of higher hopelessness. The effect is also potentially a response to a longer second interval relative to the first and is related to slower time experience. These results suggest that Vierordt central tendency effects in response to a longer second production interval than first are recruited as a Bayesian PEM strategy that utilises prior distribution based on a moving average of intervals presented previously (Shi et al., 2013).