

1 Event History Analysis for psychological time-to-event data: A tutorial in R with examples
2 in Bayesian and frequentist workflows

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Abstract

15 Time-to-event data such as response times, saccade latencies, and fixation durations form a
16 cornerstone of experimental psychology, and have had a widespread impact on our
17 understanding of human cognition. However, the orthodox method for analysing such data
18 – comparing means between conditions – is known to conceal valuable information about
19 the timeline of psychological effects, such as their onset time and duration. The ability to
20 reveal finer-grained, “temporal states” of cognitive processes can have important
21 consequences for theory development by qualitatively changing the key inferences that are
22 drawn from psychological data. Luckily, well-established analytical approaches, such as
23 event history analysis (EHA), are able to evaluate the detailed shape of time-to-event
24 distributions, and thus characterise the time course of psychological states. One barrier to
25 wider use of EHA, however, is that the analytical workflow is typically more
26 time-consuming and complex than orthodox approaches. To help achieve broader uptake,
27 in this paper we outline a set of tutorials that detail how to implement one distributional
28 method known as discrete-time EHA. We illustrate how to wrangle raw data files and
29 calculate descriptive statistics, as well as how to calculate inferential statistics via Bayesian
30 and frequentist multilevel regression modelling. Along the way, we touch upon several key
31 aspects of the workflow, such as how to specify regression models, the implications for
32 experimental design, as well as how to manage inter-individual differences. We finish the
33 article by considering the benefits of the approach for understanding psychological states,
34 as well as the limitations and future directions of this work. Finally, the project is written
35 in R and freely available, which means the general approach can easily be adapted to other
36 data sets, and all of the tutorials are available as .html files to widen access beyond R-users.

37 *Keywords:* response times, event history analysis, Bayesian multi-level regression
38 models, experimental psychology, cognitive psychology

39 Word count: X

40

1. Introduction

41 1.1 Motivation and background context: Comparing means versus 42 distributional shapes

43 In experimental psychology, it is standard practice to analyse response times (RTs),
44 saccade latencies, and fixation durations by calculating average performance across a series
45 of trials. Such mean-average comparisons have been the workhorse of experimental
46 psychology over the last century, and have had a substantial impact on theory development
47 as well as our understanding of the structure of cognition and brain function. However,
48 differences in mean RT conceal important pieces of information, such as when an
49 experimental effect starts, how long it lasts, how it evolves with increasing waiting time,
50 and whether its onset is time-locked to other events (Panis, 2020; Panis, Moran,
51 Wolkersdorfer, & Schmidt, 2020; Panis & Schmidt, 2016, 2022; Panis, Torfs, Gillebert,
52 Wagemans, & Humphreys, 2017; Panis & Wagemans, 2009; Wolkersdorfer, Panis, &
53 Schmidt, 2020). Such information is useful not only for the interpretation of experimental
54 effects under investigation, but also for cognitive psychophysiology and computational
55 model selection (Panis, Schmidt, Wolkersdorfer, & Schmidt, 2020).

56 As a simple illustration, Figure 1 shows the results of several simulated RT data sets,
57 which show how mean-average comparisons between two conditions can conceal the shape
58 of the underlying RT distributions. For instance, in examples 1-3, mean RT is always
59 comparable between two conditions, while the distributions differ (Figure 1, left). In
60 contrast, in examples 4-6, mean RT is lower in condition 2 compared to condition 1, but
61 the RT distributions differ in each case (Figure 1, right). Therefore, a comparison of means
62 would lead to a similar conclusion in examples 1-3, as well as examples 4-6, whereas a
63 comparison of the distributions would lead to a different conclusion in every case.

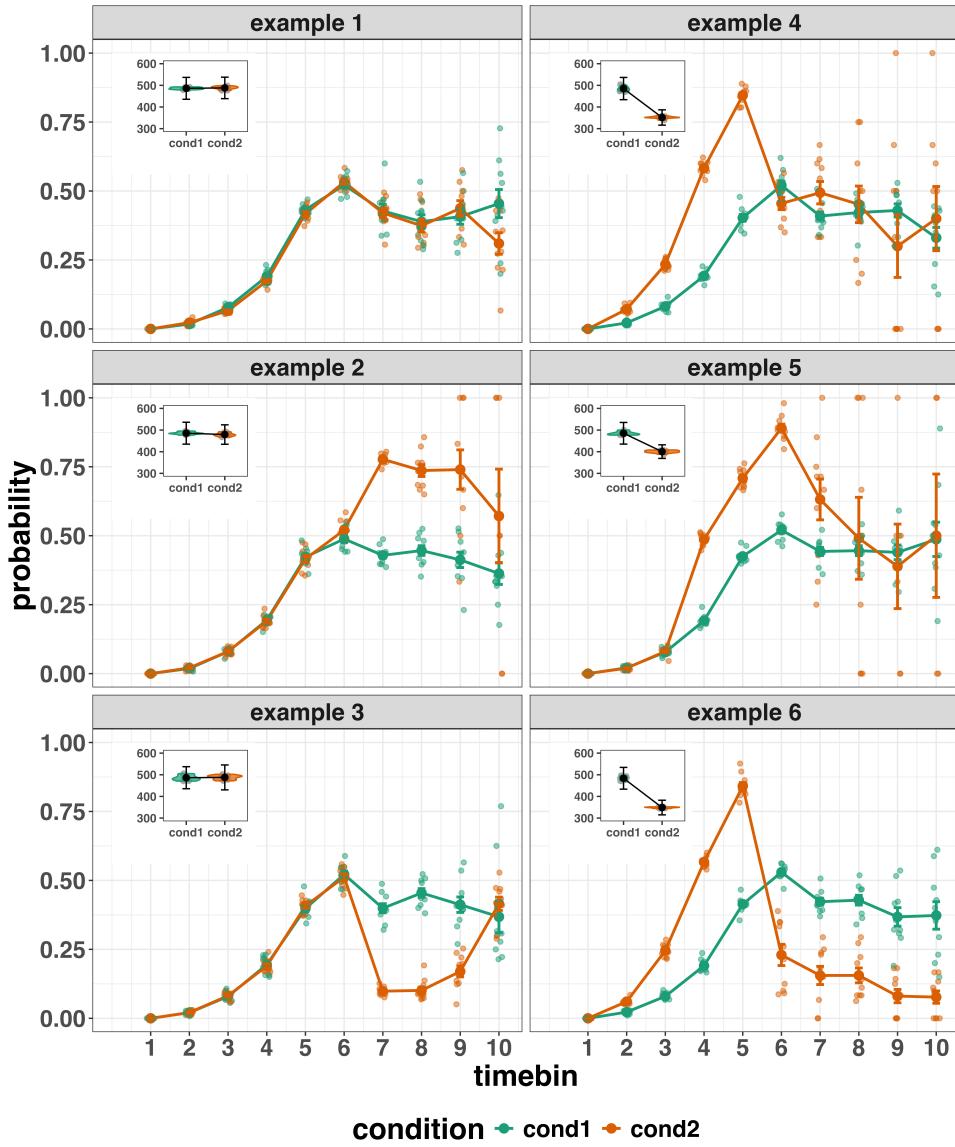


Figure 1. Means versus distributional shapes for six different simulated data set examples.

The first second after stimulus onset is divided in ten bins of 100 ms. Timebin indicates the bin rank. The first bin is (0,100], the last bin is (900,1000]. For our purposes here, it is enough to know that the distributions plotted represent the probability of an event occurring in that timebin, given that it has not yet occurred. Insets show mean response time per condition.

65 data across trials, a distributional approach offers the possibility to reveal the time course
66 of psychological states. As such, the approach permits different kinds of questions to be
67 asked, different inferences to be made, and it holds the potential to discriminate between
68 different theoretical accounts of psychological and/or brain-based processes. For example,
69 the distributions in Example 4 show that the effect starts between 100 and 200 ms (in
70 timebin 2) and is gone when the waiting time reaches 500 ms or more. In contrast, in
71 Example 5, the effect starts around 300 ms and is gone by 700 ms. And in the Example 6,
72 the effect reverses between 500 and 600 ms. What kind of theory or theories could account
73 for such effects? Are there new auxiliary assumptions that theories need to adopt? And are
74 there new experiments that need to be performed to test the novel predictions that follow
75 from these analyses? As we show later using published examples, for many psychological
76 questions, such “temporal states” information can be theoretically meaningful by leading to
77 more fine-grained understanding of psychological processes, as well as adding a relatively
78 under-used dimension – the passage of time – to the theory building toolkit.

79 From a historical perspective, it is worth noting that the development of analytical
80 tools that can estimate or predict whether and when events will occur is not a new
81 endeavour. Indeed, hundreds of years ago, analytical methods were developed to predict
82 the duration of time until people died (e.g., Halley, 1693; Makeham, 1860). The same logic
83 has been applied to psychological time-to-event data, as previously demonstrated (Panis,
84 Schmidt, et al., 2020).

85 1.2 Aims and structure of the paper

86 In this paper, we focus on a distributional method for time-to-event data known as
87 discrete-time Event History Analysis (EHA), a.k.a. survival analysis, hazard analysis,
88 duration analysis, failure-time analysis, and transition analysis (Singer & Willett, 2003).
89 We hope to show the value of EHA for knowledge and theory building in cognitive
90 psychology and related areas of research, such as cognitive neuroscience. Most importantly,

91 we provide tutorials that provide step-by-step code and instructions in the hope that we
92 can enable others to use EHA in a more routine, efficient and effective manner.

93 We first provide a brief overview of EHA to orient the reader to the basic concepts
94 that we will use throughout the paper. However, this will remain relatively short, as this
95 has been covered in detail before (Allison, 1982, 2010; Singer & Willett, 2003). Indeed, our
96 primary aim here is to introduce the set of tutorials, which explain **how** to do such
97 analyses, rather than repeat in any detail **why** you may do them.

98 We provide six different tutorials, which are written in the R programming language
99 and publicly available on our Github and the Open Science Framework (OSF) pages, along
100 with all of the other code and material associated with the project. The tutorials provide
101 hands-on, concrete examples of key parts of the analytical process, so that others can apply
102 EHA to their own time-to-event data sets. Each tutorial is provided as an RMarkdown file,
103 so that others can download and adapt the code to fit their own purposes. Additionally,
104 each tutorial is made available as a .html file, so that it can be viewed by any web browser,
105 and thus available to those that do not use R. Finally, the manuscript itself is written in R
106 using the papaja package (Aust & Barth, 2024), which makes it computationally
107 reproducible, in terms of the underlying data and figures.

108 In Tutorial 1a, we illustrate how to process or “wrangle” a previously published RT +
109 accuracy data set to calculate descriptive statistics when there is one independent variable.
110 The descriptive statistics are plotted, and we comment on their interpretation. In Tutorial
111 1b we provide a generalisation of this approach to illustrate how one can calculate the
112 descriptive statistics when using a more complex design, such as when there are two
113 independent variables.

114 In Tutorial 2a, we illustrate how one can fit Bayesian multi-level regression models to
115 RT data using the R package brms. We also perform prior predictive checks, compare
116 models, and interpret the plots of the predicted hazard functions for the selected model,

117 and the posterior distributions of our contrasts of interest. In Tutorial 2b we fit Bayesian
118 multi-level regression models to *timed* accuracy data to perform a micro-level
119 speed-accuracy tradeoff (SAT) analysis, which complements the EHA of RT data for choice
120 RT data.

121 In Tutorial 3a, we shortly illustrate how to fit similar multilevel regression models for
122 RT data in a frequentist framework using the R package lme4. We then briefly compare
123 and contrast these inferential frameworks when applied to EHA. In Tutorial 3b, we
124 illustrate how to perform the SAT analysis in a frequentist framework.

125 In tutorial 4, we illustrate one approach to planning how much data to collect in an
126 experiment using EHA. We use data simulation techniques to vary sample size and trial
127 count per condition until a certain degree of statistical power or precision is reached.
128 [[more to come here, once we have written the tutorial]].

129 In summary, even though EHA is a widely used statistical tool and there already exist
130 many excellent reviews (e.g., Blossfeld & Rohwer, 2002; Box-Steffensmeier, 2004; Hosmer,
131 Lemeshow, & May, 2011; Teachman, 1983) and tutorials (e.g., Allison, 2010; Landes,
132 Engelhardt, & Pelletier, 2020) on its general use-cases, we are not aware of any tutorials
133 that are aimed at psychological time-to-event data, and which provide worked examples of
134 the key data processing and multi-level regression modelling steps. Therefore, our ultimate
135 goal is twofold: first, we want to convince readers of the many benefits of using EHA when
136 dealing with time-to-event data with a focus on psychological time-to-event data, and
137 second, we want to provide a set of practical tutorials, which provide step-by-step
138 instructions on how you actually perform a discrete-time EHA on time-to-event data such
139 as RT data, as well as a complementary discrete-time SAT analysis on timed accuracy data.

2. A brief introduction to event history analysis

For a comprehensive background context to EHA, we recommend several excellent textbooks (Allison, 2010; Singer & Willett, 2003). Likewise, for a general introduction to understanding regression equations, we recommend several excellent textbooks (Gelman, Hill, & Vehtari, 2020; Winter, 2019). Our focus here is not on providing a detailed account of the underlying regression equations, since this topic has been comprehensively covered many times before. Instead, we want to provide an intuition regarding how EHA works in general, as well as in the context of experimental psychology. As such, we only supply regression equations in part D of the supplementary material.

2.1 Basic features of event history analysis

To apply EHA, one must be able to:

1. define an event of interest that represents a qualitative change that can be situated in time (e.g., a button press, a saccade onset, a fixation offset, etc.);
2. define time point zero (e.g., target stimulus onset, fixation onset, etc.);
3. measure the passage of time between time point zero and event occurrence in discrete or continuous time units.

In EHA, the definition of hazard and the type of models employed depend on whether one is using continuous or discrete time units. Since our focus here is on hazard models that use discrete time units, we describe that approach. After dividing time in discrete, contiguous time bins indexed by t (e.g., $t = 1:10$ timebins), let RT be a discrete random variable denoting the rank of the time bin in which a particular person's response occurs in a particular experimental condition. For example, the first response might occur at 546 ms and it would be in timebin 6 (any RTs from 501 ms to 600 ms).

163 Discrete-time EHA focuses on the discrete-time hazard function of event occurrence

164 and the discrete-time survivor function (Figure 2). The equations that define both of these

165 functions are reported in part A of the supplementary material. The discrete-time hazard

166 function gives you, for each time bin, the probability that the event occurs (sometime) in

167 bin t , given that the event does not occur in previous bins. In other words, it reflects the

168 instantaneous likelihood that the event occurs in the current bin, given that it has not yet

169 occurred in the past, i.e., in one of the prior bins. In contrast, the discrete-time survivor

170 function cumulates the bin-by-bin risks of event *nonoccurrence* to obtain the survival

171 probability, the probability that the event occurs after bin t . In other words, the survivor

172 function gives you for each time bin the likelihood that the event occurs in the future, i.e.,

173 in one of the subsequent timebins.

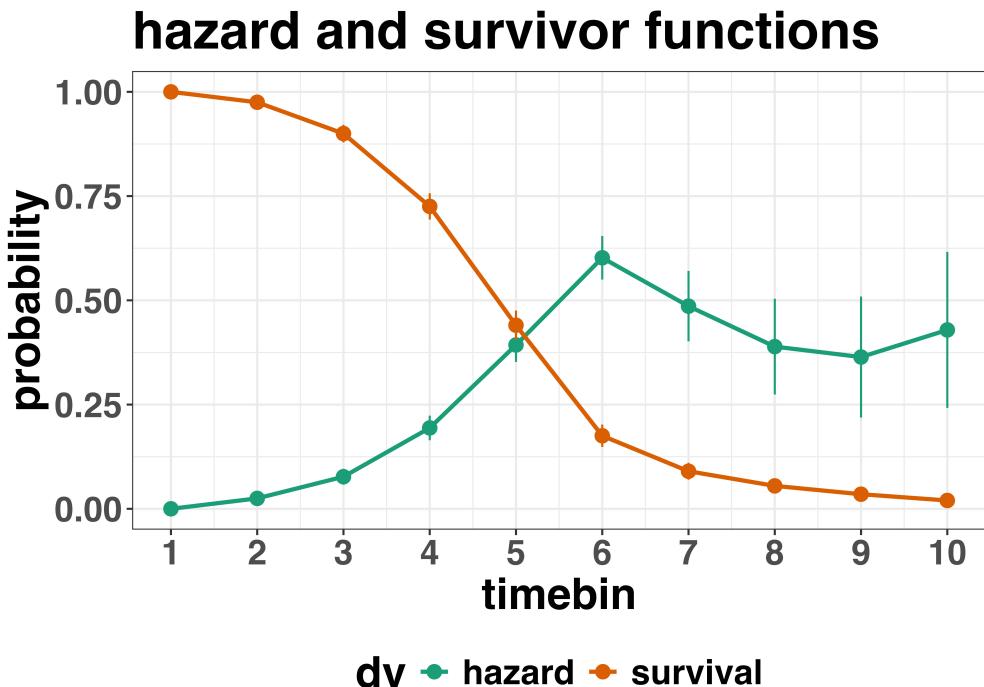


Figure 2. Discrete-time hazard and survivor functions. Discrete time-to-event data were simulated for 200 trials of 1 experimental condition. While the hazard function is the vehicle for inferring the time course of cognitive processes, the survival probability $S(t-1)$ can help to qualify or provide context to the interpretation of the hazard probability $h(t)$. For example, the high hazard of $.60 = h(t=6)$ is experienced only by 44 percent of the trials, as $S(t=5) = .44$. Because the survivor function is a decreasing function of time, the error bars in later parts of the hazard function will always be wider and less precise compared to earlier parts.

¹⁷⁴ 2.2 Benefits of event history analysis

¹⁷⁵ Statisticians and mathematical psychologists recommend focusing on the hazard
¹⁷⁶ function when analyzing time-to-event data for various reasons. We do not cover these
¹⁷⁷ benefits in detail here, as these are more general topics that have been covered elsewhere in
¹⁷⁸ textbooks. Instead, we briefly summarise list the benefits below, and refer the reader to
¹⁷⁹ section F of Supplementary Materials for more detailed coverage of the benefits. A
¹⁸⁰ summary of the benefits are as follows:

- 181 1. Hazard functions are more diagnostic than density functions when one is interested in
182 studying the detailed shape of a RT distribution (Holden et al., 2009).
- 183 2. RT distributions may differ from each other in multiple ways, and hazard functions
184 allow one to capture these differences which mean-average comparisons may conceal
185 (Townsend, 1990).
- 186 3. EHA takes account of more of the data collected in a typical speeded response
187 experiment, by virtue of not discarding right-censored observations. Trials with very
188 long RTs are not discarded, but instead contribute to the risk set in each time bin
189 (see below).
- 190 4. Hazard modeling allows one to incorporate time-varying explanatory covariates, such
191 as heart rate, electroencephalogram (EEG) signal amplitude, gaze location, etc.
192 (Allison, 2010). This is useful for linking physiological effects to behavioral effects
193 when performing cognitive psychophysiology (Meyer, Osman, Irwin, & Yantis, 1988).
- 194 5. EHA can help to solve the problem of model mimicry, i.e., the fact that different
195 computational models can often predict the same mean RTs as observed in the
196 empirical data, but not necessarily the detailed shapes of the empirical RT hazard
197 distributions. As such, EHA can be a tool to help distinguish between competing
198 theories of cognition and brain function.

199 2.3 Event history analysis in the context of experimental psychology

200 To make EHA more relevant to researchers studying cognitive psychology and

201 cognitive neuroscience, in this section we provide a relevant worked example and consider
202 implications that are relevant to that domain of research.

203 **2.3.1 A worked example.** In the context of experimental psychology, it is

204 common for participants to be presented with either a 1-button detection task or a

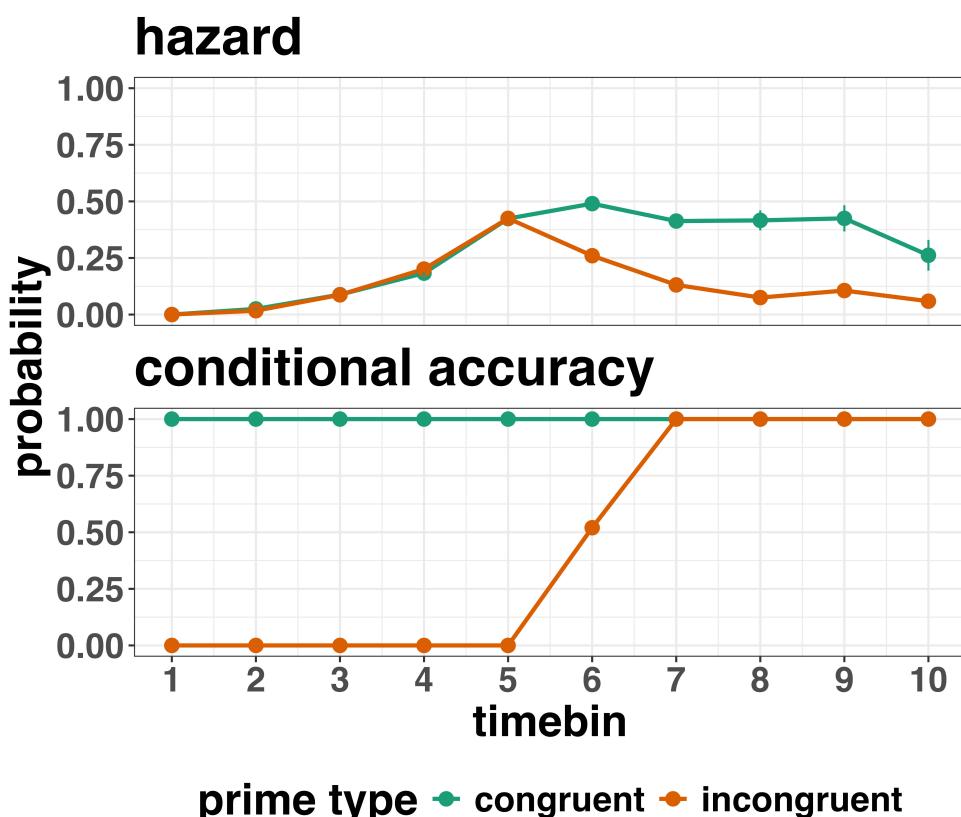
discrimination task. For example, a task may involve choosing between two response options with only one of them being correct. For such two-choice RT data, the discrete-time EHA of the RT data (hazard and survivor functions) can be extended with a discrete-time SAT analysis of the timed accuracy data. Specifically, the hazard function of event occurrence can be extended with the discrete-time conditional accuracy function, which gives you the probability that a response is correct given that it is emitted in time bin t (Allison, 2010; Kantowitz & Pachella, 2021; Wickelgren, 1977). We refer to this extended (hazard + conditional accuracy) analysis for choice RT data as EHA/SAT.

Integrating results between hazard and conditional accuracy functions for choice RT data can be informative for understanding psychological processes. To illustrate, we consider a hypothetical choice RT example that is inspired by real data (Panis & Schmidt, 2016), but simplified to make the main point clearer (Figure 3). In a standard priming paradigm, there is a prime stimulus (e.g., an arrow pointing left or right) followed by a target stimulus (another arrow pointing left or right). The prime can then be congruent or incongruent with the target.

Figure 3 shows that the early upswing in hazard is equal for both priming conditions, and that early emitted responses are always correct in the congruent condition and always incorrect in the incongruent condition. These results show that for short waiting times (< timebin 6), responses always follow the prime (and not the target, as instructed). During timebin 6 the target-triggered response channel is activated and causes response competition – $ca(6) = .5$ – and a lower hazard probability in the incongruent condition. For waiting times of 600 ms or more, the hazard of response occurrence is lower in incongruent compared to congruent trials, and all responses emitted in these late bins are correct.

This joint pattern of results is interesting because it can provide meaningfully different conclusions about psychological processes compared to conventional analyses, such as computing mean-average RT and accuracy across trials. Mean-average RT would only

231 represent the overall ability of cognition to overcome interference, on average, across trials.
 232 For instance, if mean-average RT was higher in incongruent than congruent trials, one may
 233 conclude that cognitive mechanisms that support interference control are working as
 234 expected across trials, and are indexed by each recorded response. But such a conclusion is
 235 not supported when the effects are explored over a timeline. Instead, the psychological
 236 conclusion is much more nuanced and suggests that multiple states start, stop and possibly
 237 interact over a particular temporal window.



238 Unlocking the temporal states of cognitive processes can be revealing for theory
 239 development and the understanding of basic psychological processes. Possibly more

240 importantly, however, is that it simultaneously opens the door to address many new and
241 previously unanswered questions. Do all participants show similar temporal states or are
242 there individual differences? Do such individual differences extend to those individuals that
243 have been diagnosed with some form of psychopathology? How do temporal states relate to
244 brain-based mechanisms that might be studied using other methods from cognitive
245 neuroscience? And how much of theory in cognitive psychology would be in need of
246 revision if mean-average comparisons were supplemented with a temporal states approach?

247 **2.3.2 Implications for designing experiments.** Performing EHA in
248 experimental psychology has implications for how experiments are designed. Indeed, if
249 trials are categorised as a function of when responses occur, then each timebin will only
250 include a subset of the total number of trials. For example, let's consider an experiment
251 where each participant performs 2 conditions and there are 100 trial repetitions per
252 condition. Those 100 trials must be distributed in some manner across the chosen number
253 of bins.

254 In such experimental designs, since the number of trials per condition are spread
255 across bins, it is important to have a relatively large number of trial repetitions per
256 participant and per condition. Accordingly, experimental designs using this approach
257 typically focus on factorial, within-subject designs, in which a large number of observations
258 are made on a relatively small number of participants (so-called small- N designs). This
259 approach emphasizes the precision and reproducibility of data patterns at the individual
260 participant level to increase the inferential validity of the design (Baker et al., 2021; Smith
261 & Little, 2018).

262 In contrast to the large- N design that typically average across many participants
263 without being able to scrutinize individual data patterns, small- N designs retain crucial
264 information about the data patterns of individual observers. This can be advantageous
265 whenever participants differ systematically in their strategies or in the time courses of their
266 effects, so that averaging them would lead to misleading data patterns. Note that because

267 statistical power derives both from the number of participants and from the number of
268 repeated measures per participant and condition, small- N designs can still achieve what
269 are generally considered acceptable levels of statistical power, if they have a sufficient
270 amount of data overall (Baker et al., 2021; Smith & Little, 2018).

271 **3. An overview of the general analytical workflow**

272 Although the focus is on EHA/SAT, we also want to briefly comment on broader
273 aspects of our general analytical workflow, which relate more to data science and data
274 analysis workflows.

275 **3.1 Data science workflow and descriptive statistics**

276 We perform data wrangling following tidyverse principles and a functional
277 programming approach (Wickham, Çetinkaya-Rundel, & Grolemund, 2023). Functional
278 programming basically means that you avoid writing your own loops but instead use
279 functions that have been built and tested by others. In addition, we also supply a set of
280 custom-built functions, which make the process of data wrangling in the context of
281 descriptive EHA a lot quicker and more efficient.

282 **3.2 Inferential statistical approach**

283 Our lab adopts a estimation approach to multi-level regression (Kruschke & Liddell,
284 2018; Winter, 2019), which is heavily influenced by the Bayesian framework as suggested
285 by Richard McElreath (Kurz, 2023b; McElreath, 2020). We also use a “keep it maximal”
286 approach to specifying varying (or random) effects (Barr, Levy, Scheepers, & Tily, 2013).
287 This means that wherever possible we include varying intercepts and slopes per participant
288 To make inferences, we use two main approaches. We compare models of different
289 complexity, using information criteria (e.g., WAIC) and cross-validation (e.g., LOO), to

290 evaluate out-of-sample predictive accuracy (McElreath, 2020). We also take the most
291 complex model and evaluate key parameters of interest using point and interval estimates.

292 **3.3 Implementation**

293 We used R (Version 4.4.0; R Core Team, 2024)¹ for all reported analyses. The
294 content of the tutorials, in terms of EHA and multi-level regression modelling, is mainly
295 based on Allison (2010), Singer and Willett (2003), McElreath (2020), Heiss (2021), Kurz
296 (2023a), and Kurz (2023b).

297 **4. Tutorials**

298 Tutorials 1a and 1b show how to calculate and plot the descriptive statistics of
299 EHA/SAT when there are one and two independent variables, respectively. Tutorials 2a
300 and 2b illustrate how to use Bayesian multilevel modeling to fit hazard and conditional
301 accuracy models, respectively. Tutorials 3a and 3b show how to implement, respectively,
302 multilevel models for hazard and conditional accuracy in the frequentist framework.

¹ We, furthermore, used the R-packages *bayesplot* (Version 1.11.1; Gabry, Simpson, Vehtari, Betancourt, & Gelman, 2019), *brms* (Version 2.21.0; Bürkner, 2017, 2018, 2021), *citr* (Version 0.3.2; Aust, 2019), *cmdstanr* (Version 0.8.1.9000; Gabry, Češnovar, Johnson, & Brønner, 2024), *dplyr* (Version 1.1.4; Wickham, François, Henry, Müller, & Vaughan, 2023), *forcats* (Version 1.0.0; Wickham, 2023a), *ggplot2* (Version 3.5.1; Wickham, 2016), *lme4* (Version 1.1.35.5; Bates, Mächler, Bolker, & Walker, 2015), *lubridate* (Version 1.9.3; Grolemund & Wickham, 2011), *Matrix* (Version 1.7.0; Bates, Maechler, & Jagan, 2024), *nlme* (Version 3.1.166; Pinheiro & Bates, 2000), *papaja* (Version 0.1.2.9000; Aust & Barth, 2023), *patchwork* (Version 1.2.0; Pedersen, 2024), *purrr* (Version 1.0.2; Wickham & Henry, 2023), *RColorBrewer* (Version 1.1.3; Neuwirth, 2022), *Rcpp* (Eddelbuettel & Balamuta, 2018; Version 1.0.12; Eddelbuettel & François, 2011), *readr* (Version 2.1.5; Wickham, Hester, & Bryan, 2024), *RJ-2021-048* (Bengtsson, 2021), *standist* (Version 0.0.0.9000; Girard, 2024), *stringr* (Version 1.5.1; Wickham, 2023b), *tibble* (Version 3.2.1; Müller & Wickham, 2023), *tidybayes* (Version 3.0.6; Kay, 2023), *tidyrr* (Version 1.3.1; Wickham, Vaughan, & Girlich, 2024), *tidyverse* (Version 2.0.0; Wickham et al., 2019), and *tinylabels* (Version 0.2.4; Barth, 2023).

303 Additionally, to further simplify the process for other users, the first two tutorials rely on a
304 set of our own custom functions that make sub-processes easier to automate, such as data
305 wrangling and plotting functions (see part B in the supplemental material for a list of the
306 custom functions).

307 Our list of tutorials is as follows:

- 308 • 1a. Wrangle raw data and calculate descriptive stats for one independent variable
- 309 • 1b. Wrangle raw data and calculate descriptive stats for two independent variables
- 310 • 2a. Bayesian multilevel modeling for $h(t)$
- 311 • 2b. Bayesian multilevel modeling for $ca(t)$
- 312 • 3a. Frequentist multilevel modeling for $h(t)$
- 313 • 3b. Frequentist multilevel modeling for $ca(t)$
- 314 • 4. Simulation and power analysis for planning experiments

315 **4.1 Tutorial 1a: Calculating descriptive statistics using a life table**

316 **4.1.1 Data wrangling aims.** Our data wrangling procedures serve two related
317 purposes. First, we want to summarise and visualise descriptive statistics that relate to our
318 main research questions about the time course of psychological processes, using a life table.
319 A life table includes for each time bin, the risk set (i.e., the number of trials that are
320 event-free at the start of the bin), the number of observed events, and the estimates of
321 $h(t)$, $S(t)$, $P(t)$, possibly $ca(t)$, and their estimated standard errors (se).

322 Second, we want to produce two different data sets that can each be submitted to
323 different types of inferential modelling approaches. The two types of data structure we
324 label as ‘person-trial’ data and ‘person-trial-bin’ data. The ‘person-trial’ data (Table 1)
325 will be familiar to most researchers who record behavioural responses from participants, as
326 it represents the measured RT and accuracy per trial within an experiment. This data set
327 is used when fitting conditional accuracy models (Tutorials 2b and 3b).

Table 1
Data structure for ‘person-trial’ data

pid	trial	condition	rt	accuracy
1	1	congruent	373.49	1
1	2	incongruent	431.31	1
1	3	congruent	455.43	0
1	4	incongruent	622.41	1
1	5	incongruent	535.98	1
1	6	incongruent	540.08	1
1	7	congruent	511.07	1
1	8	incongruent	444.42	1
1	9	congruent	678.69	1
1	10	congruent	549.79	1

Note. The first 10 trials for participant 1 are shown. These data are simulated and for illustrative purposes only.

328 In contrast, the ‘person-trial-bin’ data (Table 2) has a different, more extended
 329 structure, which indicates in which bin a response occurred, if at all, in each trial.
 330 Therefore, the ‘person-trial-bin’ data set generates a 0 in each bin until an event occurs
 331 and then it generates a 1 to signal an event has occurred in that bin. This data set is used
 332 when fitting hazard models (Tutorials 2a and 3a). It is worth pointing out that there is no
 333 requirement for an event to occur at all (in any bin), as maybe there was no response on
 334 that trial or the event occurred after the time window of interest. Likewise, when the event
 335 occurs in bin 1 there would only be one row of data for that trial in the person-trial-bin
 336 data set.

Table 2
Data structure for ‘person-trial-bin’ data

pid	trial	condition	timebin	event
1	1	congruent	1	0
1	1	congruent	2	0
1	1	congruent	3	0
1	1	congruent	4	1
1	2	incongruent	1	0
1	2	incongruent	2	0
1	2	incongruent	3	0
1	2	incongruent	4	0
1	2	incongruent	5	1

Note. The first 2 trials for participant 1 from Table 1 are shown. The width of the time bins is 100 ms. These data are simulated and for illustrative purposes only.

337 **4.1.2 A real data wrangling example.** To illustrate how to quickly set up life
 338 tables for calculating the descriptive statistics (functions of discrete time), we use a
 339 published data set on masked response priming from Panis and Schmidt (2016). In their
 340 first experiment, Panis and Schmidt (2016) presented a double arrow for 94 ms that
 341 pointed left or right as the target stimulus with an onset at time point zero in each trial.
 342 Participants had to indicate the direction in which the double arrow pointed using their
 343 corresponding index finger, within 800 ms after target onset. Response time and accuracy
 344 were recorded on each trial. Prime type (blank, congruent, incongruent) and mask type
 345 were manipulated. Here we focus on the subset of trials in which no mask was presented.

346 The 13-ms prime stimulus was a double arrow presented 187 ms before target onset in the
 347 congruent (same direction as target) and incongruent (opposite direction as target) prime
 348 conditions.

349 There are several data wrangling steps to be taken. First, we need to load the data
 350 before we (a) supply required column names, and (b) specify the factor condition with the
 351 correct levels and labels.

352 The required column names are as follows:

- 353 • “pid”, indicating unique participant IDs;
- 354 • “trial”, indicating each unique trial per participant;
- 355 • “condition”, a factor indicating the levels of the independent variable (1, 2, ...) and
 356 the corresponding labels;
- 357 • “rt”, indicating the response times in ms;
- 358 • “acc”, indicating the accuracies (1/0).

359 In the code of Tutorial 1a, this is accomplished as follows.

```
data_wr<-read_csv("../Tutorial_1_descriptive_stats/data/DataExp1_6subjects_wrangled.csv")
colnames(data_wr) <- c("pid","bl","tr","condition","resp","acc","rt","trial")
data_wr <- data_wr %>%
  mutate(condition = condition + 1, # original levels were 0, 1, 2.
        condition = factor(condition,
                             levels=c(1,2,3),
                             labels=c("blank","congruent","incongruent")))
```

360 Next, we can set up the life tables and plots of the discrete-time functions $h(t)$, $S(t)$,
 361 $ca(t)$, and $P(t)$ – see part A of the supplementary material for their definitions. To do so
 362 using a functional programming approach, one has to nest the data within participants
 363 using the `group_nest()` function, and supply a user-defined censoring time and bin width
 364 to our custom function “`censor()`”, as follows.

```

data_nested <- data_wr %>% group_nest(pid)

data_final <- data_nested %>%
  # ! user input: censoring time, and bin width
  mutate(censored = map(data, censor, 600, 40)) %>%
  # create person-trial-bin data set
  mutate(ptb_data = map(censored, ptb)) %>%
  # create life tables without ca(t)
  mutate(lifetable = map(ptb_data, setup_lt)) %>%
  # calculate ca(t)
  mutate(condacc = map(censored, calc_ca)) %>%
  # create life tables with ca(t)
  mutate(lifetable_ca = map2(lifetable, condacc, join_lt_ca)) %>%
  # create plots
  mutate(plot = map2(.x = lifetable_ca, .y = pid, plot_eha,1))

```

365 Note that the censoring time should be a multiple of the bin width (both in ms). The
 366 censoring time should be a time point after which no informative responses are expected
 367 anymore. In experiments that implement a response deadline in each trial the censoring
 368 time can equal that deadline time point. Trials with a RT larger than the censoring time,
 369 or trials in which no response is emitted during the data collection period, are treated as
 370 right-censored observations in EHA. In other words, these trials are not discarded, because
 371 they contain the information that the event did not occur before the censoring time.
 372 Removing such trials before calculating the mean event time will result in underestimation
 373 of the true mean.

374 The person-trial-bin oriented data set is created by our custom function ptb(), and it
 375 has one row for each time bin (of each trial) that is at risk for event occurrence. The
 376 variable “event” in the person-trial-bin oriented data set indicates whether a response
 377 occurs (1) or not (0) for each bin.

378 The next step is to set up the life table using our custom function setup_lt(),

379 calculate the conditional accuracies using our custom function `calc_ca()`, add the `ca(t)`
380 estimates to the life table using our custom function `join_lt_ca()`, and then plot the
381 descriptive statistics using our custom function `plot_eha()`. When creating the plots, some
382 warning messages will likely be generated, like these:

- 383 • Removed 2 rows containing missing values or values outside the scale range
384 (`geom_line()`).
385 • Removed 2 rows containing missing values or values outside the scale range
386 (`geom_point()`).
387 • Removed 2 rows containing missing values or values outside the scale range
388 (`geom_segment()`).

389 The warning messages are generated because some bins have no hazard and `ca(t)`
390 estimates, and no error bars. They can thus safely be ignored. One can now inspect
391 different aspects, including the life table for a particular condition of a particular subject,
392 and a plot of the different functions for a particular participant. In general, it is important
393 to visually inspect the functions first for each participant, in order to identify individuals
394 that may be guessing (e.g., a flat conditional accuracy function at .5 indicates that
395 someone is just guessing), outlying individuals, and/or different groups with qualitatively
396 different behavior.

397 Table 3 shows the life table for condition “blank” (no prime stimulus presented) for
398 participant 6.

Table 3

The life table for the blank prime condition of participant 6.

bin	risk_set	events	hazard	se_haz	survival	se_surv	ca	se_ca
0	220	NA	NA	NA	1.00	0.00	NA	NA
40	220	0	0.00	0.00	1.00	0.00	NA	NA
80	220	0	0.00	0.00	1.00	0.00	NA	NA
120	220	0	0.00	0.00	1.00	0.00	NA	NA
160	220	0	0.00	0.00	1.00	0.00	NA	NA
200	220	0	0.00	0.00	1.00	0.00	NA	NA
240	220	0	0.00	0.00	1.00	0.00	NA	NA
280	220	7	0.03	0.01	0.97	0.01	0.29	0.17
320	213	13	0.06	0.02	0.91	0.02	0.77	0.12
360	200	26	0.13	0.02	0.79	0.03	0.92	0.05
400	174	40	0.23	0.03	0.61	0.03	1.00	0.00
440	134	48	0.36	0.04	0.39	0.03	0.98	0.02
480	86	37	0.43	0.05	0.22	0.03	1.00	0.00
520	49	32	0.65	0.07	0.08	0.02	1.00	0.00
560	17	9	0.53	0.12	0.04	0.01	1.00	0.00
600	8	4	0.50	0.18	0.02	0.01	1.00	0.00

Note. The column named “bin” indicates the endpoint of each time bin (in ms), and includes time point zero. For example the first bin is (0,40] with the starting point excluded and the endpoint included. At time point zero, no events can occur and therefore $h(t=0)$ and $ca(t=0)$ are undefined. $se =$ standard error. $ca =$ conditional accuracy. $NA =$ undefined.

Figure 4 displays the discrete-time hazard, survivor, conditional accuracy, and

400 probability mass functions for each prime condition for participant 6. By using
 401 discrete-time hazard functions of event occurrence – in combination with conditional
 402 accuracy functions for two-choice tasks – one can provide an unbiased, time-varying, and
 403 probabilistic description of the latency and accuracy of responses based on all trials of any
 404 data set.

Descriptive stats for subject 6

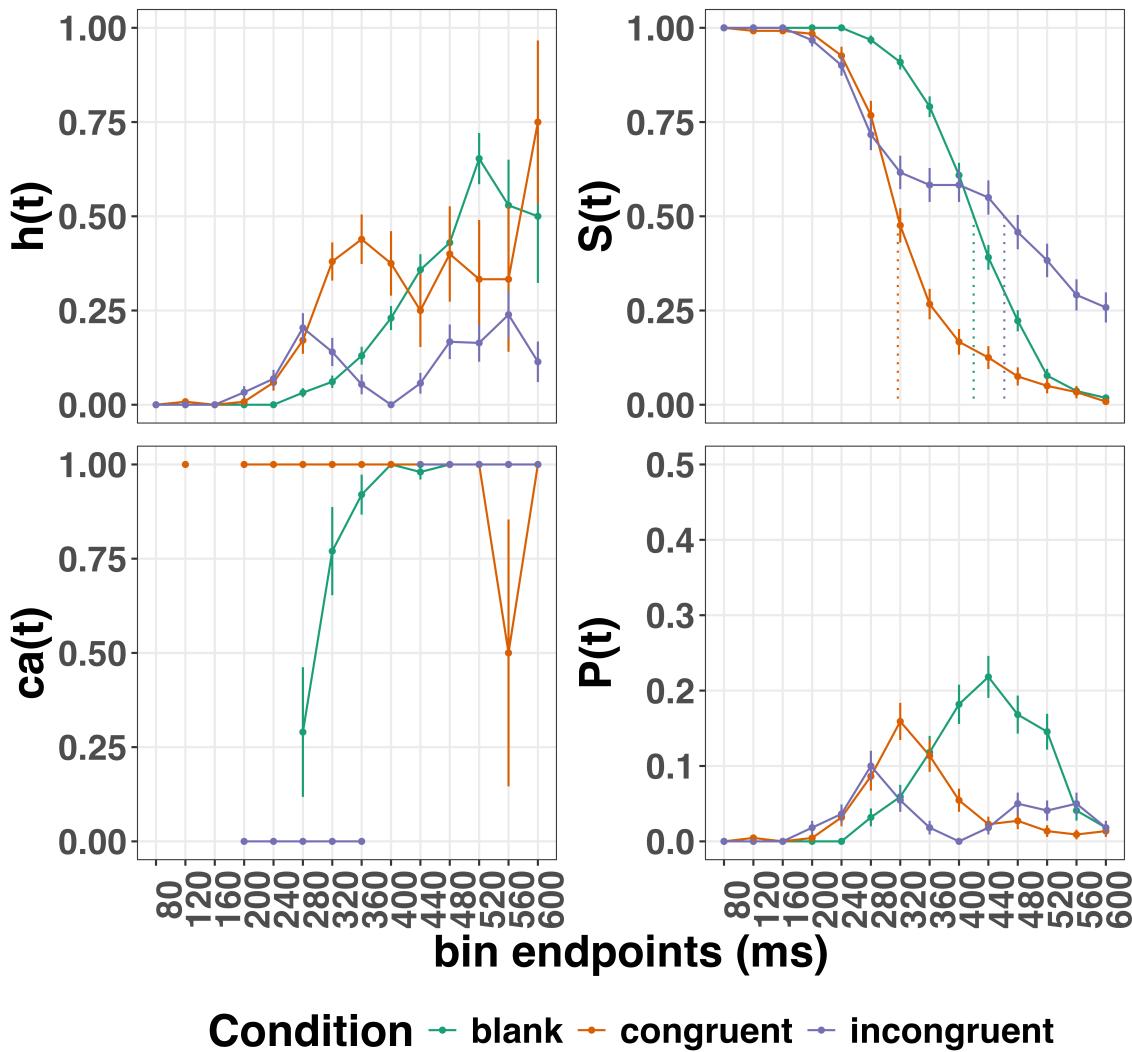


Figure 4. Estimated discrete-time hazard, survivor, probability mass, and conditional accuracy functions for participant 6. Vertical dotted lines indicate the estimated median RTs. Error bars represent +/- 1 Standard Error of the respective proportion.

405 For example, for participant 6, the estimated hazard values in bin (240,280] are 0.03,

406 0.17, and 0.20 for the blank, congruent, and incongruent prime conditions, respectively. In

407 other words, when the waiting time has increased until *240 ms* after target onset, then the

408 conditional probability of response occurrence in the next 40 ms is more than five times

409 larger for both prime-present conditions, compared to the blank prime condition.

410 Furthermore, the estimated conditional accuracy values in bin (240,280] are 0.29, 1,

411 and 0 for the blank, congruent, and incongruent prime conditions, respectively. In other

412 words, if a response is emitted in bin (240,280], then the probability that it is correct is

413 estimated to be 0.29, 1, and 0 for the blank, congruent, and incongruent prime conditions,

414 respectively.

415 However, when the waiting time has increased until *400 ms* after target onset, then

416 the conditional probability of response occurrence in the next 40 ms is estimated to be

417 0.36, 0.25, and 0.06 for the blank, congruent, and incongruent prime conditions,

418 respectively. And when a response does occur in bin (400,440], then the probability that it

419 is correct is estimated to be 0.98, 1, and 1 for the blank, congruent, and incongruent prime

420 conditions, respectively.

421 These distributional results suggest that the participant 6 is initially responding to

422 the prime even though (s)he was instructed to only respond to the target, that response

423 competition emerges in the incongruent prime condition around 300 ms, and that only

424 slower responses are fully controlled by the target stimulus. Qualitatively similar results

425 were obtained for the other five participants. When participants show qualitatively the

426 same distributional patterns, one might consider to aggregate their data and make one plot

427 (see Tutorial_1a.Rmd).

428 In general, these results go against the (often implicit) assumption in research on

429 priming that all observed responses are primed responses to the target stimulus. Instead,

430 the distributional data show that early responses are triggered exclusively by the prime

431 stimulus, while only later responses reflect primed responses to the target stimulus.

432 At this point, we have calculated, summarised and plotted descriptive statistics for
433 the key variables in EHA/SAT. As we will show in later Tutorials, statistical models for
434 $h(t)$ and $ca(t)$ can be implemented as generalized linear mixed regression models predicting
435 event occurrence (1/0) and conditional accuracy (1/0) in each bin of a selected time
436 window for analysis. But first we consider calculating the descriptive statistics for two
437 independent variables.

438 **4.2 Tutorial 1b: Generalising to a more complex design**

439 So far in this paper, we have used a simple experimental design, which involved one
440 condition with three levels. But psychological experiments are often more complex, with
441 crossed factorial designs with more conditions and more than three levels. The purpose of
442 Tutorial 1b, therefore, is to provide a generalisation of the basic approach, which extends
443 to a more complicated design. We felt that this might be useful for researchers in
444 experimental psychology that typically use crossed factorial designs.

445 To this end, Tutorial 1b illustrates how to calculate and plot the descriptive statistics
446 for the full data set of Experiment 1 of Panis and Schmidt (2016), which includes two
447 independent variables: mask type and prime type. As we use the same functional
448 programming approach as in Tutorial 1a, we simply present the sample-based functions for
449 each participant as part of Tutorial_1b.Rmd for those that are interested.

450 **4.3 Tutorial 2a: Fitting Bayesian hazard models to discrete time-to-event data**

451 In this third tutorial, we illustrate how to fit Bayesian multi-level regression models
452 to the RT data of the masked response priming data set used in Tutorial 1a. Fitting
453 (Bayesian or non-Bayesian) regression models to time-to-event data is important when you
454 want to study how the shape of the hazard function depends on various predictors (Singer

455 & Willett, 2003).

456 **4.3.1 Hazard model considerations.** There are several analytic decisions one
457 has to make when fitting a discrete-time hazard model. First, one has to select an analysis
458 time window, i.e., a contiguous set of bins for which there is enough data for each
459 participant. Second, given that the dependent variable (event occurrence) is binary, one
460 has to select a link function (see part C in the supplementary material). The cloglog link is
461 preferred over the logit link when events can occur in principle at any time point within a
462 bin, which is the case for RT data (Singer & Willett, 2003). Third, one has to choose
463 whether to treat TIME (i.e., the time bin index t) as a categorical or continuous predictor.
464 And when you treat a variable as a categorical predictor, you can choose between reference
465 coding and index coding. With reference coding, one defines the variable as a factor and
466 selects one of the k categories as the reference level. Brm() will then construct $k-1$
467 indicator variables (see model M1d in Tutorial_2a.Rmd for an example). With index
468 coding, one constructs an index variable which contains integers that correspond to
469 different categories (see models M0i and M1i below). As explained by McElreath (2020),
470 the advantage of index coding is that the same prior can be assigned to each level of the
471 index variable, so that each category has the same prior uncertainty.

472 In the case of a large- N design without repeated measurements, the parameters of a
473 discrete-time hazard model can be estimated using standard logistic regression software
474 after expanding the typical person-trial data set into a person-trial-bin data set (Allison,
475 2010). When there is clustering in the data, as in the case of a small- N design with
476 repeated measurements, the parameters of a discrete-time hazard model can be estimated
477 using population-averaged methods (e.g., Generalized Estimating Equations), and Bayesian
478 or frequentist generalized linear mixed models (Allison, 2010).

479 In general, there are three assumptions one can make or relax when adding
480 experimental predictor variables and other covariates: The linearity assumption for
481 continuous predictors (the effect of a 1 unit change is the same anywhere on the scale), the

482 additivity assumption (predictors do not interact), and the proportionality assumption
 483 (predictors do not interact with TIME).

484 In tutorial_2a.Rmd we fit several Bayesian multilevel models (i.e., generalized linear
 485 mixed models) that differ in complexity to the person-trial-bin oriented data set that we
 486 created in Tutorial 1a. We decided to select the analysis time window (200,600] and the
 487 cloglog link. Below, we shortly discuss two of these models. The person-trial-bin data set is
 488 prepared as follows.

```
# read in the file we saved in tutorial 1a
ptb_data <- read_csv("Tutorial_1_descriptive_stats/data/inputfile_hazard_modeling.csv")

ptb_data <- ptb_data %>%
  # select analysis time range: (200,600] with 10 bins (time bin ranks 6 to 15)
  filter(period > 5) %>%
    # define categorical predictor TIME as index variable named timebin
  mutate(timebin = factor(period, levels = c(6:15)),
    # factor "condition" using reference coding, with "blank" as the reference level
    condition = factor(condition, labels = c("blank", "congruent", "incongruent")),
    # categorical predictor "prime" with index coding
    prime = ifelse(condition=="blank", 1, ifelse(condition=="congruent", 2, 3)),
    prime = factor(prime, levels = c(1,2,3)))
```

489 **4.3.2 Prior distributions.** To get the posterior distribution of each model
 490 parameter given the data, we need to specify prior distributions for the model parameters
 491 which reflect our prior beliefs. In Tutorial_2a.Rmd we perform a few prior predictive
 492 checks to make sure our selected prior distributions reflect our prior beliefs (Gelman,
 493 Vehtari, et al., 2020).

494 The middle column of Figure 16 in part E of the supplementary material shows six
 495 examples of prior distributions for an intercept on the logit and/or cloglog scales. While a
 496 normal distribution with relatively large variance is often used as a weakly informative

497 prior for continuous dependent variables, rows A and B in Figure 16 show that specifying
 498 such distributions on the logit and cloglog scales actually leads to rather informative
 499 distributions on the original probability scale, as most mass is pushed to probabilities of 0
 500 and 1.

501 **4.3.3 Model M0i: A null model with index coding.** When you do not want to
 502 make assumptions about the shape of the hazard function, or its shape is not smooth but
 503 irregular, then you can use a general specification of TIME, i.e., fit one grand intercept per
 504 time bin. In this first model, we use a general specification of TIME using index coding,
 505 and do not include experimental predictors. We call this model “M0i”.

506 Before we fit model M0i, we select the necessary columns from the data, and specify
 507 our priors. In the code of Tutorial 2a, model M0i is specified as follows.

```
model_M0i <-
  brm(data = data_M0i,
       family = bernoulli(link="cloglog"),
       formula = event ~ 0 + timebin + (0 + timebin | pid),
       prior = priors_M0i,
       chains = 4, cores = 4,
       iter = 3000, warmup = 1000,
       control = list(adapt_delta = 0.999,
                      step_size = 0.04,
                      max_treedepth = 12),
       seed = 12, init = "0",
       file = "Tutorial_2_Bayesian/models/model_M0i")
```

508 After selecting the bernoulli family and the cloglog link, the model formula is
 509 specified. The specification “ $0 + \dots$ ” removes the default intercept in brm(). The fixed
 510 effects include an intercept for each level of timebin. Each of these intercepts is allowed to

511 vary across individuals (variable pid). We request 2000 samples from the posterior
 512 distribution for each of four chains. Estimating model M0i took about 30 minutes on a
 513 MacBook Pro (Sonoma 14.6.1 OS, 18GB Memory, M3 Pro Chip).

514 **4.3.4 Model M1i: Adding the effects of prime-target congruency.** Previous
 515 research has shown that psychological effects typically change over time (Panis, 2020;
 516 Panis, Moran, et al., 2020; Panis & Schmidt, 2022; Panis et al., 2017; Panis & Wagemans,
 517 2009). In the next model, therefore, we use index coding for both TIME (variable
 518 “timebin”) and the categorical predictor prime-target-congruency (variable “prime”), so
 519 that we get 30 grand intercepts, one for each combination of timebin level and prime level.
 520 Here is the model formula of this model that we call “M1i”.

```
event ~ 0 + timebin:prime + (0 + timebin:prime | pid)
```

521 Estimating model M1i took about 124 minutes.

522 **4.3.5 Compare the models.** We can compare the two models using the Widely
 523 Applicable Information Criterion (WAIC) and Leave-One-Out (LOO) cross-validation, and
 524 look at model weights for both criteria (Kurz, 2023a; McElreath, 2020).

```
model_weights(model_M0i, model_M1i, weights = "loo") %>% round(digits = 2)
```

525 ## model_M0i model_M1i
 526 ## 0 1

```
model_weights(model_M0i, model_M1i, weights = "waic") %>% round(digits = 2)
```

527 ## model_M0i model_M1i
 528 ## 0 1

529 Clearly, both the loo and waic weighting schemes assign a weight of 1 to model M1i,
 530 and a weight of 0 to the other simpler model.

531 **4.3.6 Evaluating parameter estimates in model M1i.** To make inferences

532 from the parameter estimates in model M1i, we first plot the densities of the draws from
 533 the posterior distributions of its population-level parameters in Figure 5, together with
 534 point (median) and interval estimates (80% and 95% credible intervals).

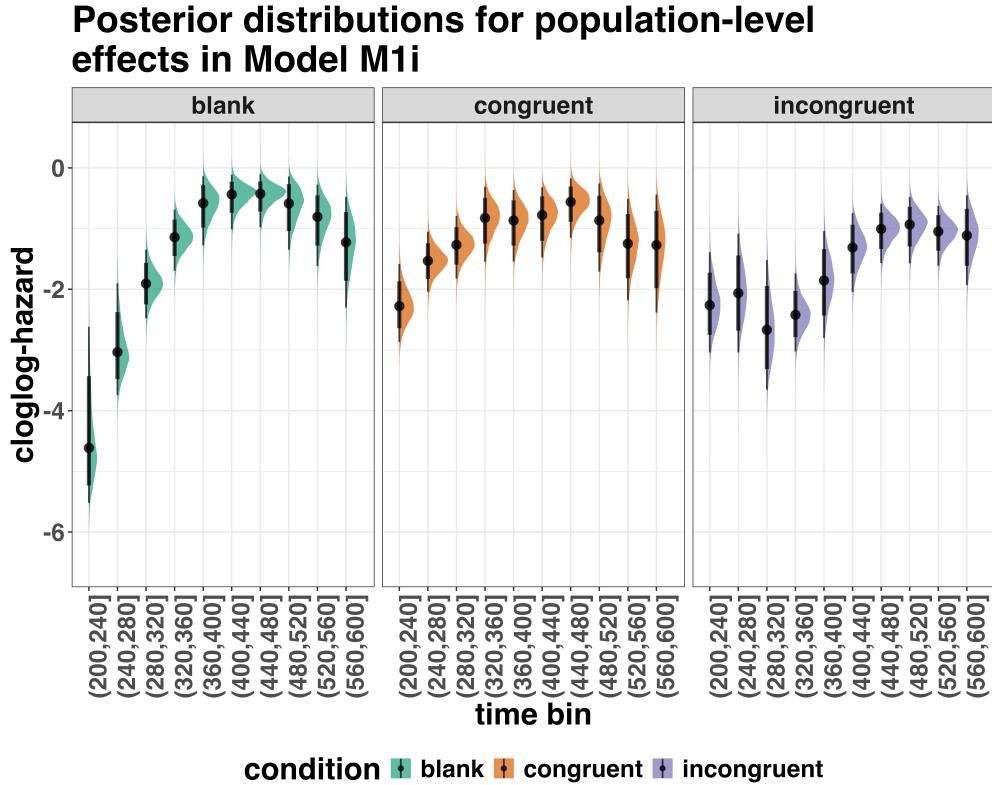


Figure 5. Medians and 80/95% credible intervals of the posterior distributions of the population-level parameters of model M1i.

535 Because the parameter estimates are on the cloglog-hazard scale, we can ease our

536 interpretation by plotting the expected value of the posterior predictive distribution – the
 537 predicted hazard values – for the average participant (Figure 6), and for each participant in
 538 the data set (Figure 7).

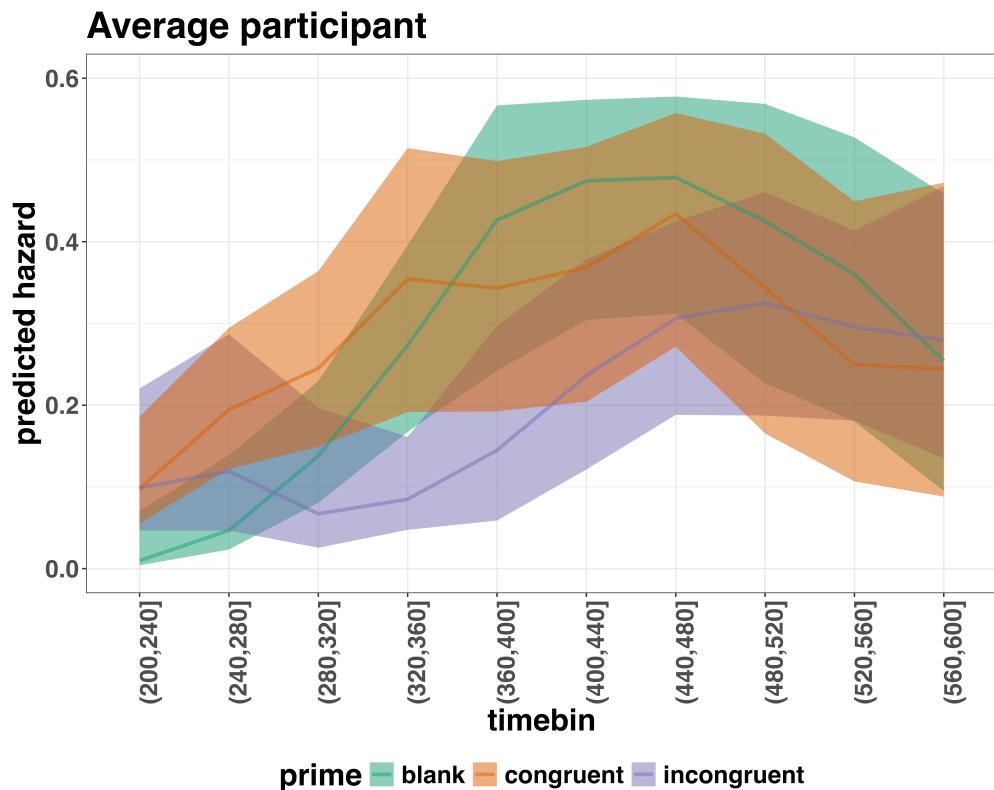


Figure 6. Point (median) and 80/95% credible interval summaries of the hazard estimates (expected values of the draws from the posterior predictive distributions) in each time bin for the average participant.

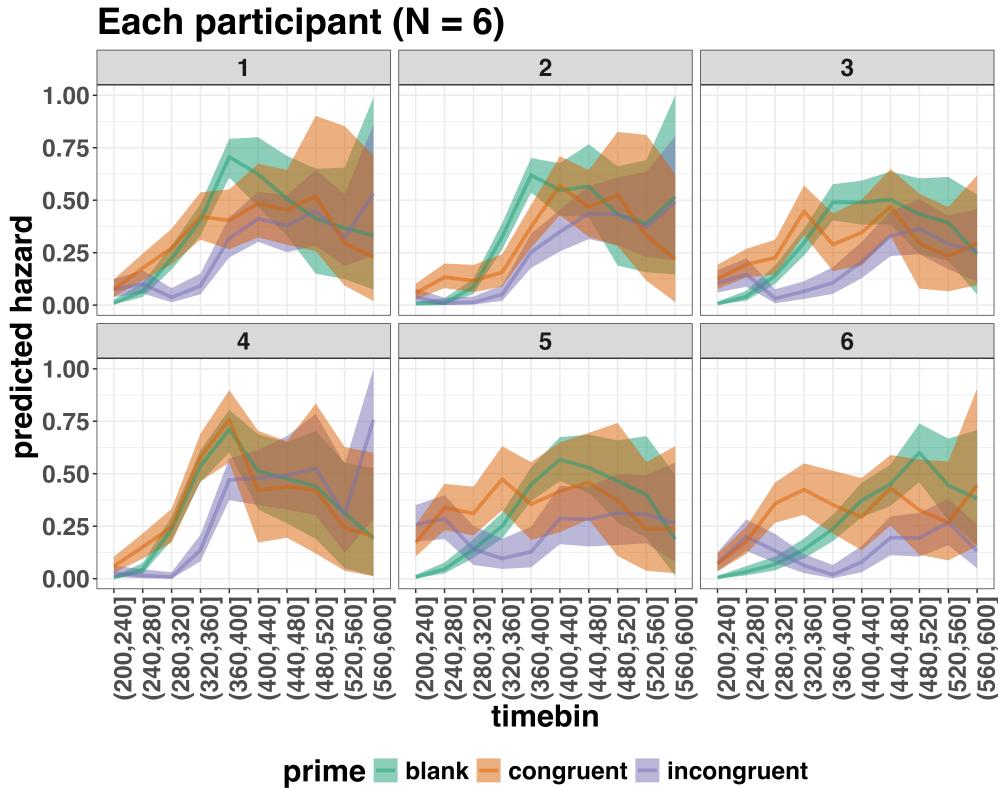


Figure 7. Point (median) and 80/95% credible interval summaries of the hazard estimates (expected values of the draws from the posterior predictive distributions) in each time bin for each participant.

539 As we are actually interested in the effects of congruent and incongruent primes,

540 relative to the blank prime condition, we can construct two contrasts (congruent-blank,

541 incongruent-blank), and plot the posterior distributions of these contrast effects, both for

542 the average participant (Figure 8; grand average marginal effect) and for each participant

543 in the data set (Figure 9; subject-specific average marginal effect).

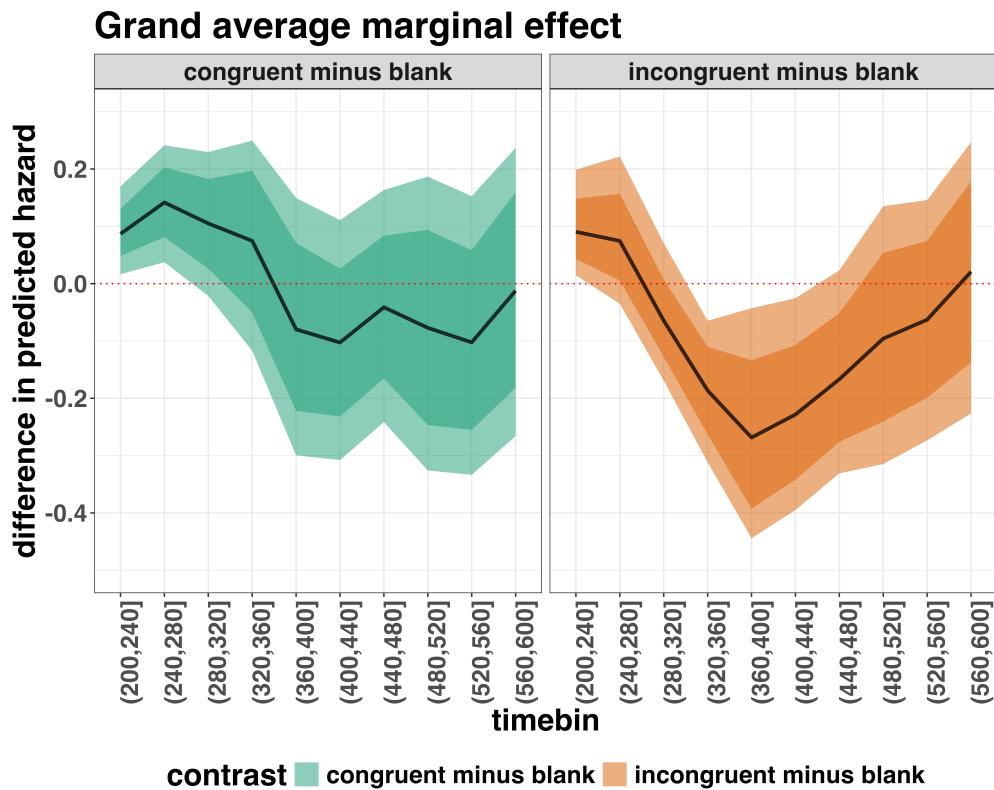


Figure 8. Point (mean) and 80/95% credible interval summaries of estimated differences in hazard in each time bin for the average participant.

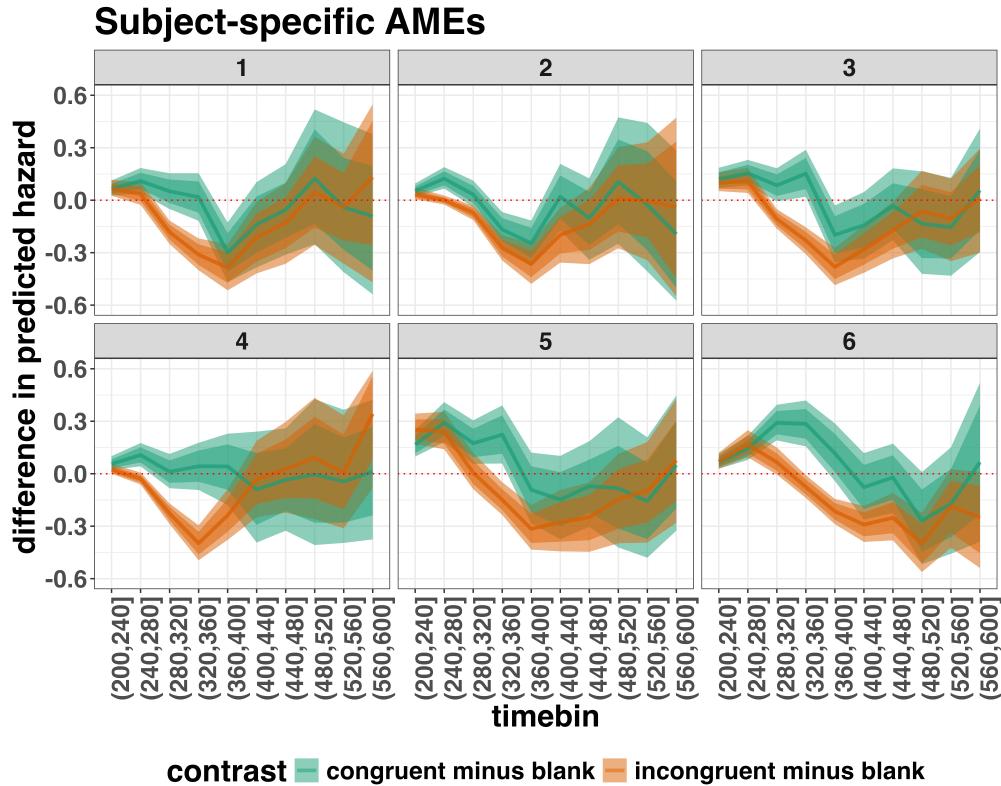


Figure 9. Point (mean) and 80/95% credible interval summaries of estimated differences in hazard in each time bin for each participant.

544 Table 4 shows the summaries of the estimated hazard differences for both contrasts in
 545 terms of a point estimate (the mean) and the upper and lower bounds of the 95% credible
 546 interval, for the average participant.

547 **Example conclusions for M1i.** What can we conclude from model M1i about
 548 our research question, i.e., the temporal dynamics of the effect of prime-target congruency
 549 on RT? In other words, in which of the 40-ms time bins between 200 and 600 ms after
 550 target onset does changing the prime from blank to congruent or incongruent affect the
 551 hazard of response occurrence (for a prime-target SOA of 187 ms)?

552 If we want to study the average effect of prime type on hazard, uncontaminated by
 553 inter-individual differences, we can base our conclusion on Figure 8 and Table 4. The
 554 contrast “congruent minus blank” was estimated to be 0.09 hazard units in bin 6 (95% CrI

555 = [0.02, 0.17]), and 0.14 hazard units in bin 7 (95% CrI = [0.04, 0.25]). For the other bins,
 556 the 95% credible interval contained zero. The contrast “incongruent minus blank” was
 557 estimated to be 0.09 hazard units in bin 6 (95% CrI = [0.01, 0.21]), -0.19 hazard units in
 558 bin 9 (95% CrI = [-0.31, -0.06]), -0.27 hazard units in bin 10 (95% CrI = [-0.45, -0.04]),
 559 and -0.23 hazard units in bin 11 (95% CrI = [-0.40, -0.03]). For the other bins, the 95%
 560 credible interval contained zero. Note that we could also have calculated hazard ratios
 561 instead of hazard differences.

562 There are thus two phases of performance for the average person between 200 and
 563 600 ms after target onset. In the first phase, the addition of a congruent or incongruent
 564 prime stimulus increases the hazard of response occurrence compared to blank prime trials
 565 in the time period (200, 240]. In the second phase, only the incongruent prime decreases
 566 the hazard of response occurrence compared to blank primes, in the time period (320,440].
 567 The sign of the effect of incongruent primes on the hazard of response occurrence thus
 568 depends on how much waiting time has passed since target onset.

569 The posterior distribution of each contrast can also be summarized by considering its
 570 proportion below or above some value, like zero. Table 5 shows the proportion of the
 571 posterior distribution below or above zero, for each time bin and contrast.

Table 4

*Summarizing the posterior distributions of each contrast by their
 proportion below and above zero.*

timebin	contrast	prop_above	prop_below
6	congruent minus blank	0.99	0.01
7	congruent minus blank	0.99	0.01
8	congruent minus blank	0.95	0.05
9	congruent minus blank	0.79	0.21

Table 4 continued

timebin	contrast	prop_above	prop_below
10	congruent minus blank	0.24	0.76
11	congruent minus blank	0.15	0.85
12	congruent minus blank	0.33	0.67
13	congruent minus blank	0.28	0.72
14	congruent minus blank	0.19	0.81
15	congruent minus blank	0.47	0.53
6	incongruent minus blank	0.98	0.02
7	incongruent minus blank	0.92	0.08
8	incongruent minus blank	0.12	0.88
9	incongruent minus blank	0.00	1.00
10	incongruent minus blank	0.01	0.99
11	incongruent minus blank	0.02	0.98
12	incongruent minus blank	0.04	0.96
13	incongruent minus blank	0.20	0.80
14	incongruent minus blank	0.27	0.73
15	incongruent minus blank	0.58	0.42

Note. prop_below = proportion below zero; prop_above = proportion above zero.

572

573 Thus, the probability that the contrast “congruent minus blank” is larger than 0, is
 574 larger than .9 in bins 6 to 8. And the probability that the contrast “incongruent minus
 575 blank” is smaller than 0, is larger than .9 in bins 9 to 12.

576 If we want to focus more on inter-individual differences, we can study the
577 subject-specific hazard functions in Figure 9. Note that three participants (1, 2, and 3)
578 show a negative difference for the contrast “congruent minus incongruent” in bin (360,400]
579 – subject 2 also in bin (320,360].

580 Future studies could (a) increase the number of participants to estimate the
581 proportion of “dippers” in the subject population, and/or (b) try to explain why this dip
582 occurs. For example, Panis and Schmidt (2016) concluded that active, top-down,
583 task-guided response inhibition effects emerge around 360 ms after the onset of the stimulus
584 following the prime (here: the target stimulus). Such a top-down inhibitory effect might
585 exist in our priming data set, because after some time participants will learn that the first
586 stimulus is not the one they have to respond to. To prevent a premature overt response to
587 the prime they thus might gradually increase a global response threshold during the
588 remainder of the experiment, which could result in a lower hazard in congruent trials
589 compared to blank trials, for bins after ~360 ms, and towards the end of the experiment.
590 This effect might be masked for incongruent primes by the response competition effect.

591 Interestingly, all subjects show a tendency in their mean difference (congruent minus
592 blank) to “dip” around that time (Figure 9). Therefore, future modeling efforts could
593 incorporate the trial number into the model formula, in order to also study how the effects
594 of prime type on hazard change on the long experiment-wide time scale, next to the short
595 trial-wide time scale. In Tutorial_2a.Rmd we provide a number of model formula that
596 should get you going.

597 4.4 Tutorial 2b: Fitting Bayesian conditional accuracy models

598 In this fourth tutorial, we illustrate how to fit a Bayesian multi-level regression model
599 to the timed accuracy data from the masked response priming data set used in Tutorial 1a.
600 The general process is similar to Tutorial 2a, except that (a) we use the person-trial data

601 set, (b) we use the logit link function, and (c) we change the priors. To keep the tutorial
 602 short, we only fitted the effects of model M1i (see Tutorial 2a) in the conditional accuracy
 603 model called M1i_ca.

604 To make inferences from the parameter estimates in model M1i_ca, we first plot the
 605 densities of the draws from the posterior distributions of its population-level parameters in
 606 Figure 10, together with point (median) and interval estimates (80% and 95% credible
 607 intervals).

Posterior distributions for population-level effects in Model M1i_ca

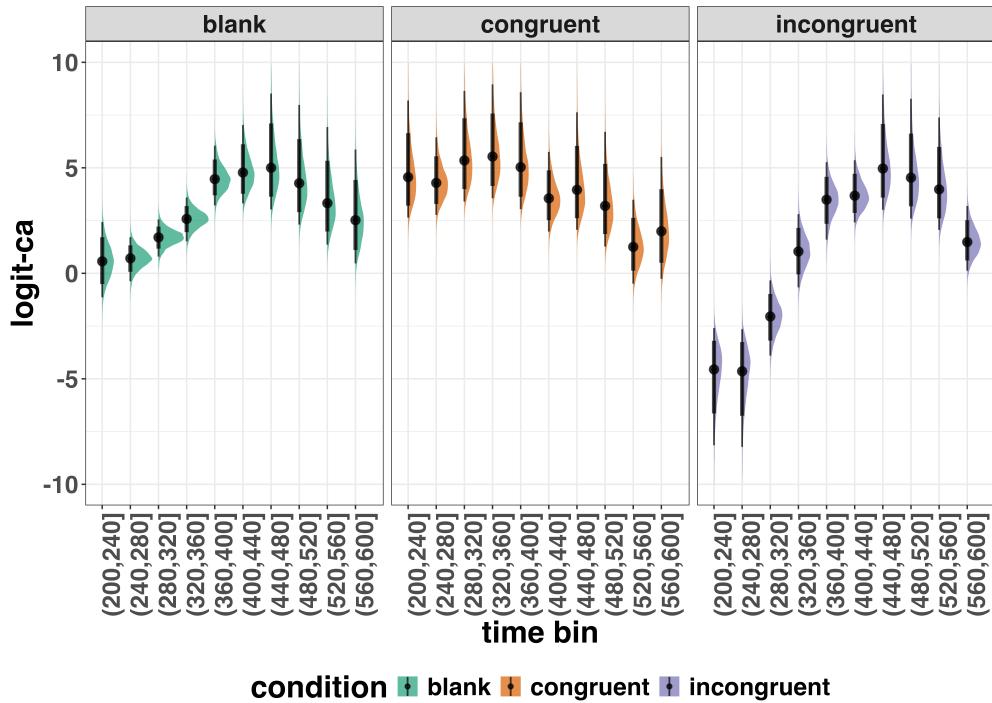


Figure 10. Medians and 80/95% credible intervals of the posterior distributions of the population-level parameters of model M1i_ca.

608 Because the parameter estimates are on the logit-ca scale, we can ease our
 609 interpretation by plotting the expected value of the posterior predictive distribution – the
 610 predicted conditional accuracies – for the average participant (Figure 11), and for each
 611 participant in the data set (Figure 12).

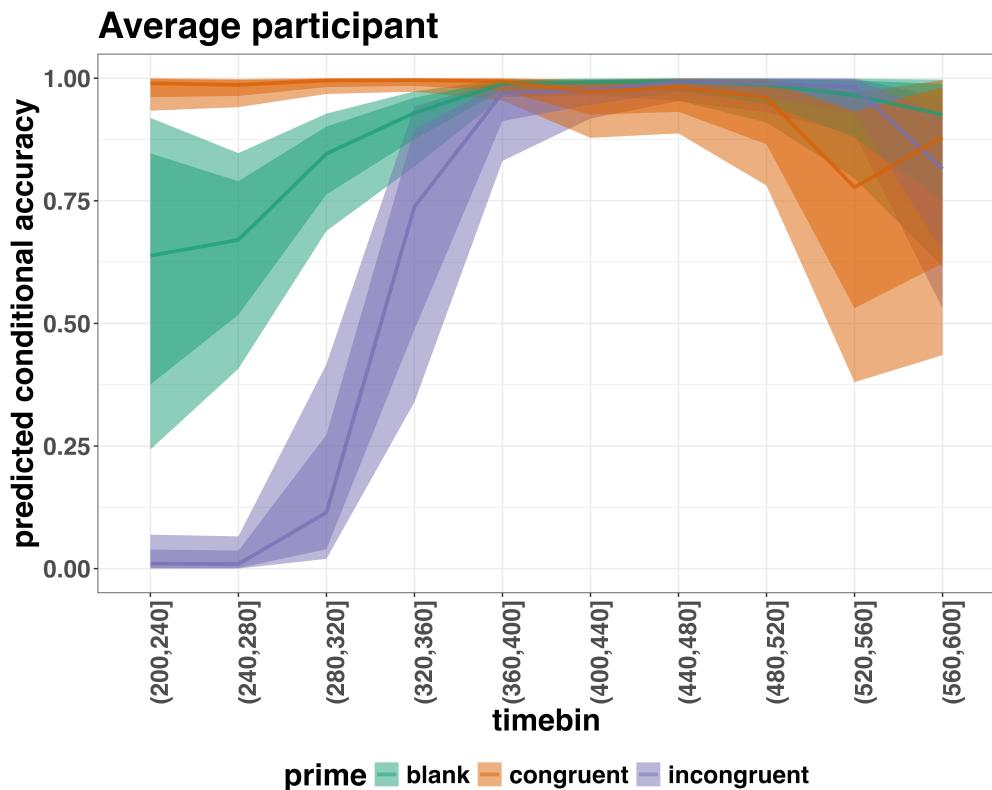


Figure 11. Point (median) and 80/95% credible interval summaries of the conditional accuracy estimates (expected values of the draws from the posterior predictive distributions) in each time bin for the average participant.

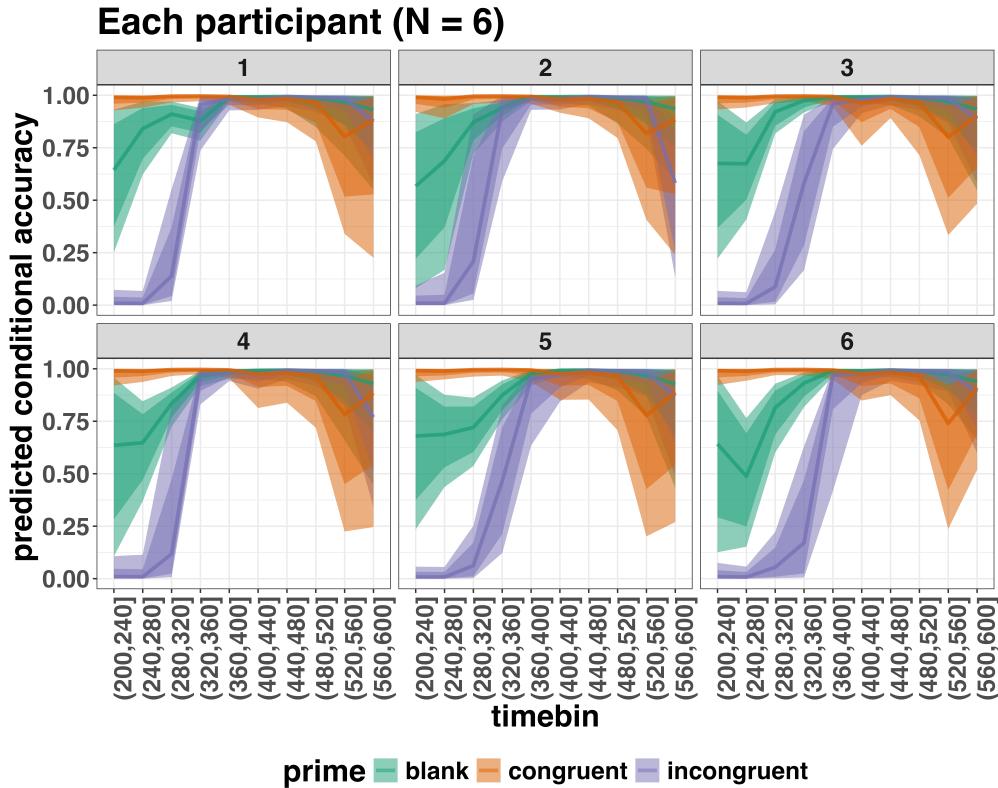


Figure 12. Point (median) and 80/95% credible interval summaries of the conditional accuracy estimates (expected values of the draws from the posterior predictive distributions) in each time bin for each participant.

As we are actually interested in the effects of congruent and incongruent primes,

relative to the blank prime condition, we can construct two contrasts (congruent-blank, incongruent-blank), and plot the posterior distributions of these contrast effects for the average participant (Figure 13; grand average marginal effect).

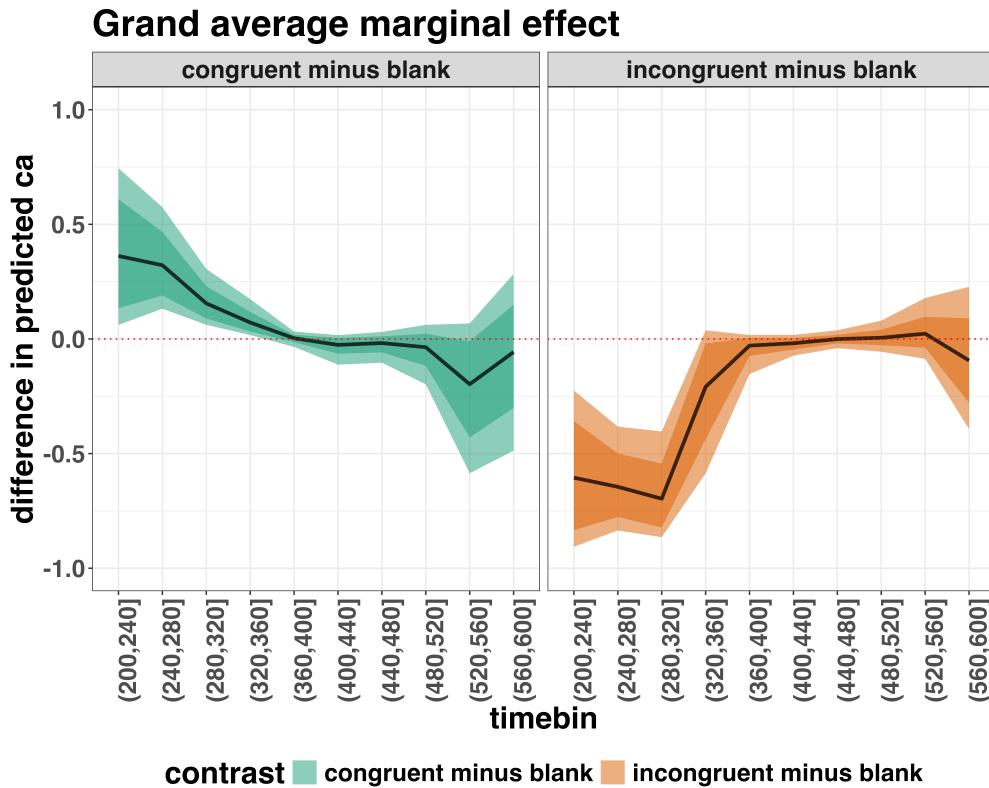


Figure 13. Point (mean) and 80/95% credible interval summaries of estimated differences in conditional accuracy in each time bin for the average participant.

616 Table 6 shows the summaries of the estimated differences in conditional accuracy for
 617 both contrasts in terms of a point estimate (the mean) and the upper and lower bounds of
 618 the 95% credible interval, for the average participant.

Table 5

Point (mean) and 95% credible interval summary of estimated differences in conditional accuracy, for each time bin and contrast, in the average participant.

contrast	timebin	diff_ca	.lower	.upper
congruent minus blank	6	0.36	0.06	0.74

Table 5 continued

contrast	timebin	diff_ca	.lower	.upper
congruent minus blank	7	0.32	0.13	0.57
congruent minus blank	8	0.16	0.06	0.31
congruent minus blank	9	0.07	0.02	0.17
congruent minus blank	10	0.00	-0.03	0.03
congruent minus blank	11	-0.03	-0.11	0.02
congruent minus blank	12	-0.02	-0.10	0.03
congruent minus blank	13	-0.04	-0.20	0.06
congruent minus blank	14	-0.20	-0.59	0.07
congruent minus blank	15	-0.06	-0.49	0.28
incongruent minus blank	6	-0.61	-0.91	-0.22
incongruent minus blank	7	-0.64	-0.84	-0.38
incongruent minus blank	8	-0.70	-0.86	-0.40
incongruent minus blank	9	-0.21	-0.59	0.04
incongruent minus blank	10	-0.03	-0.15	0.02
incongruent minus blank	11	-0.02	-0.07	0.02
incongruent minus blank	12	0.00	-0.04	0.04
incongruent minus blank	13	0.01	-0.06	0.08
incongruent minus blank	14	0.02	-0.09	0.18
incongruent minus blank	15	-0.09	-0.39	0.23

Note. diff = difference in predicted conditional accuracy.

621 on the conditional accuracy of emitted responses in time bins (200,240], (240,280], and
622 (280,320], relative to the estimates in the baseline condition (blank prime; red dashed lines
623 in Figure 14). Incongruent primes have a negative effect on the conditional accuracy of
624 emitted responses in those time bins, relative to the estimates in the baseline condition.

625 **4.5 Tutorial 3a: Fitting Frequentist hazard models**

626 In this fifth tutorial we illustrate how to fit a multilevel regression model to RT data
627 in the frequentist framework, for the data set used in Tutorial 1a. The general process is
628 similar to that in Tutorial 2a, except that there are no priors to set.

629 To keep this tutorial short, we only fitted the effects from model M1i (see Tutorial
630 2a) using the function `glmer()` from the R package `lme4`. Alternatively, one could also use
631 the function `glmmPQL()` from the R package `MASS` (Ripley et al., 2024). The resulting
632 hazard model is called `M1i_f`.

633 In Figure 14 we compare the parameter estimates of model M1i from `brm()` with
634 those of model `M1i_f` from `glmer()`.

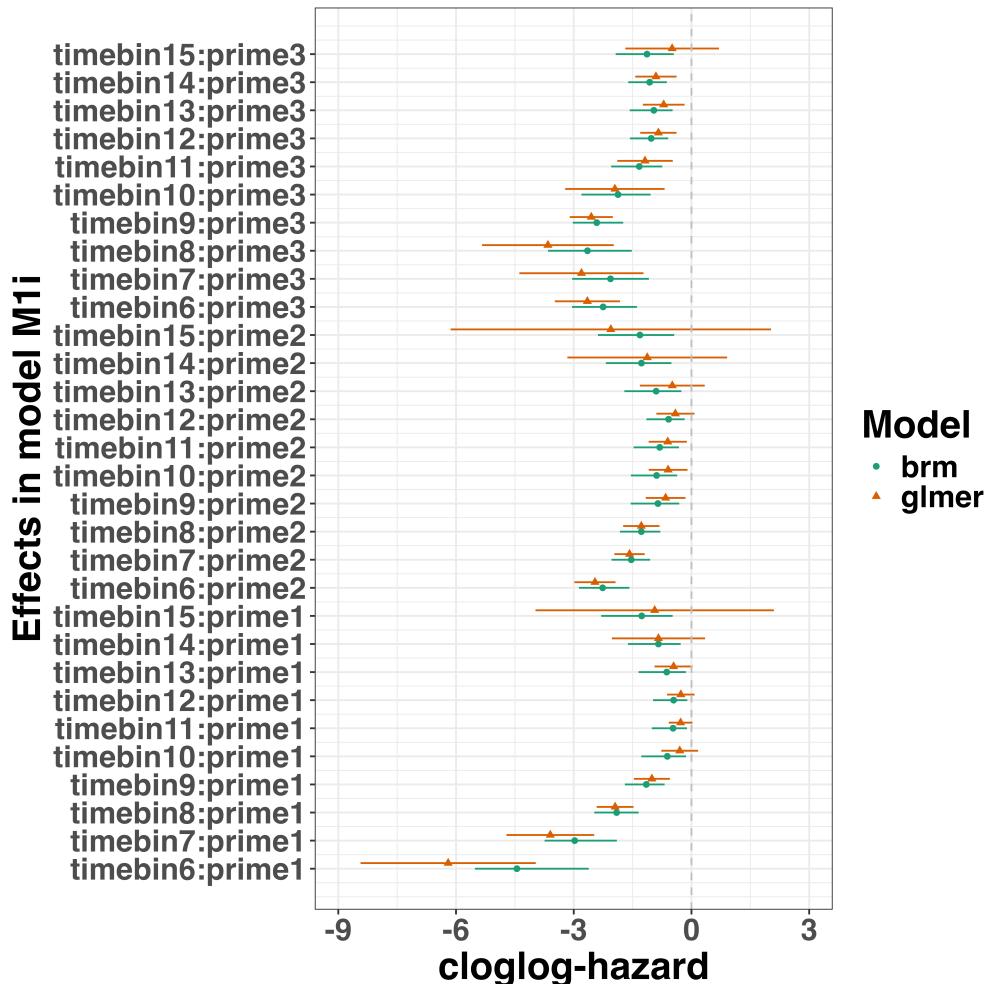


Figure 14. Parameter estimates for model M1i from `brm()` – means and 95% credible intervals – and model M1i_f from `glmer()` – maximum likelihood estimates and 95% confidence intervals.

635 Figure 14 confirms that the parameter estimates from both Bayesian and frequentist

636 models are pretty similar, which makes sense given the close similarity in model structure.

637 However, model M1i_f did not converge and resulted in a singular fit. This is of course one

638 of the reasons why Bayesian modeling has become so popular in recent years. But the price

639 you pay for being able to fit more complex random effects models in a Bayesian framework

640 is computation time. In other words, as we have noted throughout, some of the Bayesian

641 models in Tutorials 2a took several hours to build.

642 **4.6 Tutorial 3b: Fitting Frequentist conditional accuracy models**

643 In this sixth tutorial we illustrate how to fit a multilevel regression model to the
644 timed accuracy data in the frequentist framework, for the data set used in Tutorial 1a. To
645 keep it short, we only fitted the effects from model M1i_ca (see Tutorial 2b) using the
646 function glmer() from the R package lme4. Alternatively, one could also use the function
647 glmmPQL() from the R package MASS (Ripley et al., 2024). Again, the resulting
648 conditional accuracy model M1i_ca_f did not converge and resulted in a singular fit.

649 **4.7 Tutorial 4: Planning**

650 In the final tutorial, we look at planning a future experiment, which uses EHA.

651 **4.7.1 Background.** The general approach to planning that we adopt here involves
652 simulating data to help guide what you might be able to expect from your data once you
653 collect it (Gelman, Vehtari, et al., 2020). The basic structure and code follows the
654 examples outlined by Solomon Kurz in his ‘power’ blog posts
655 (<https://solomonkurz.netlify.app/blog/bayesian-power-analysis-part-i/>) and Lisa
656 Debruine’s R package faux{} (<https://debruine.github.io/faux/>) as well as the related
657 paper (DeBruine & Barr, 2021).

658 **4.7.2 Basic workflow.** The basic workflow is as follows:

- 659 1. Fit a regression model to an existing dataset.
- 660 2. Use the regression model parameters to simulate one new dataset.
- 661 3. Write a function to create 1000s of datasets and vary parameters of interest (e.g.,
662 sample size, trial count, effect size).
- 663 4. Summarise the simulated data to estimate likely power or precision of the research
664 design options.

665 Ideally, in the above workflow, we would also fit a model to each dataset and
666 summarise the model output, rather than the raw data. However, when each model takes
667 several hours to build, and we may want to simulate 1000s of datasets, it can be
668 computationally demanding for desktop machines. So, for ease, here we just use the raw
669 simulated datasets to guide future expectations.

670 In the below, we only provide a high-level summary of the process and let readers

671 dive into the details within the tutorial should they feel so inclined.

672 **4.7.3 Fit a regression model and simulate one dataset.** We again use the
673 data from Panis and Schmidt (2016) to provide a worked example. We fit an index coding
674 model on a subset of timebins (six timebins in total) and for two prime conditions
675 (congruent and incongruent). We chose to focus on a subsample of the data to ease the
676 computational burden. We also used a full varying effects structure, with the model
677 formula, as follows:

```
event ~ 0 + timebin:prime + (0 + timebin:prime | pid)
```

678 We then took parameters from this model and used them to create a single dataset

679 with 200 trials per condition for 10 individual participants. The raw data and the

680 simulated data are plotted in Figure 15 and show quite close correspondence, which is

681 re-assuring. But, this is only one dataset. What we really want to do is simulate many

682 datasets and vary parameters of interest, which is what we turn to in the next section.

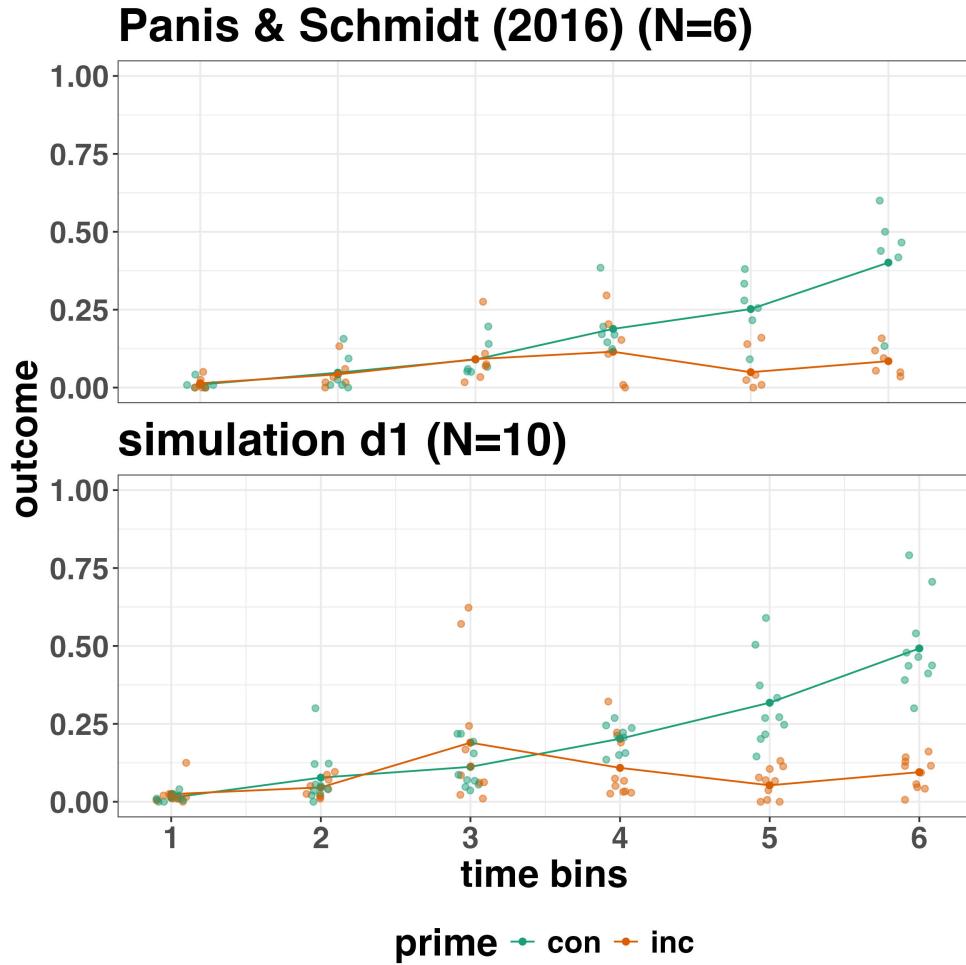


Figure 15. Raw data from Panis and Schmidt (2016) and simulated data from 10 participants.

4.7.4 Simulate and summarise data across a range of parameter values.

Here we use the same data simulation process as used above, but instead of simulating one dataset, we simulate 1000 datasets per variation in parameter values. Specifically, in Simulation 1, we vary the number of trials per condition (100, 200, and 400), as well as the effect size in bin 6. We focus on bin 6 only, in terms of varying the effect size, just to make things simpler and easier to understand. The effect size observed in bin 6 in this subsample of data was a 79% reduction in hazard value from the congruent prime (0.401 hazard value) to the incongruent prime condition (0.085 hazard value). In other words, a hazard

ratio of 0.21 (e.g., $0.085/0.401 = 0.21$). As a starting point, we chose three effect sizes, which covered a fairly broad range of hazard ratios (0.25, 0.5, 0.75), which correspond to a 75%, 50% and 25% reduction in hazard value as a function of prime condition.

Summary results from Simulation 1 are shown in Figure 16A. Figure 16A depicts statistical “power” as calculated by the percentage of lower-bound 95% confidence intervals that exclude zero when the difference between prime condition is calculated (congruent - incongruent). In other words, what fraction of the simulated datasets generated an effect of prime that excludes the criterion mark of zero. We are aware that “power” is not part of a Bayesian analytical workflow, but we choose to include it here, as it is familiar to most researchers in experimental psychology.

The results of Simulation 1 show that if we were targeting an effect size similar to the one reported in the original study, then testing 10 participants and collecting 100 trials per condition would be enough to provide over 95% power. However, we could not be as confident about smaller effects, such as a hazard ratio of 50% or 25%. From this simulation, we can see that somewhere between an effect size of a 50% and 75% reduction in hazard value, power increases to a range that most researchers would consider acceptable (i.e., >95% power). To probe this space a little further, we decided to run a second simulation, which varied different parameters

In Simulation 2, we varied the effect size between a different range of values (0.5, 0.4, 0.3), which correspond to a 50%, 60% and 70% reduction in hazard value as a function of prime condition. In addition, we varied the number of participants per experiment between 10, 15, and 20 participants. Given that trial count per condition made little difference to power in Simulation 1, we fixed trial count at 200 trials per condition in Simulation 2. Summary results from Simulation 2 are shown in Figure 16B. A summary of these power calculations might be as follows (trial count = 200 per condition in all cases):

- For a 70% reduction (0.3 hazard ratio), N=10 would give nearly 100% power.

- 717 • For a 60% reduction (0.4 hazard ratio), N=10 would give nearly 90% power.
- 718 • For a 50% reduction (0.5 hazard ratio), N=15 would give over 80% power.

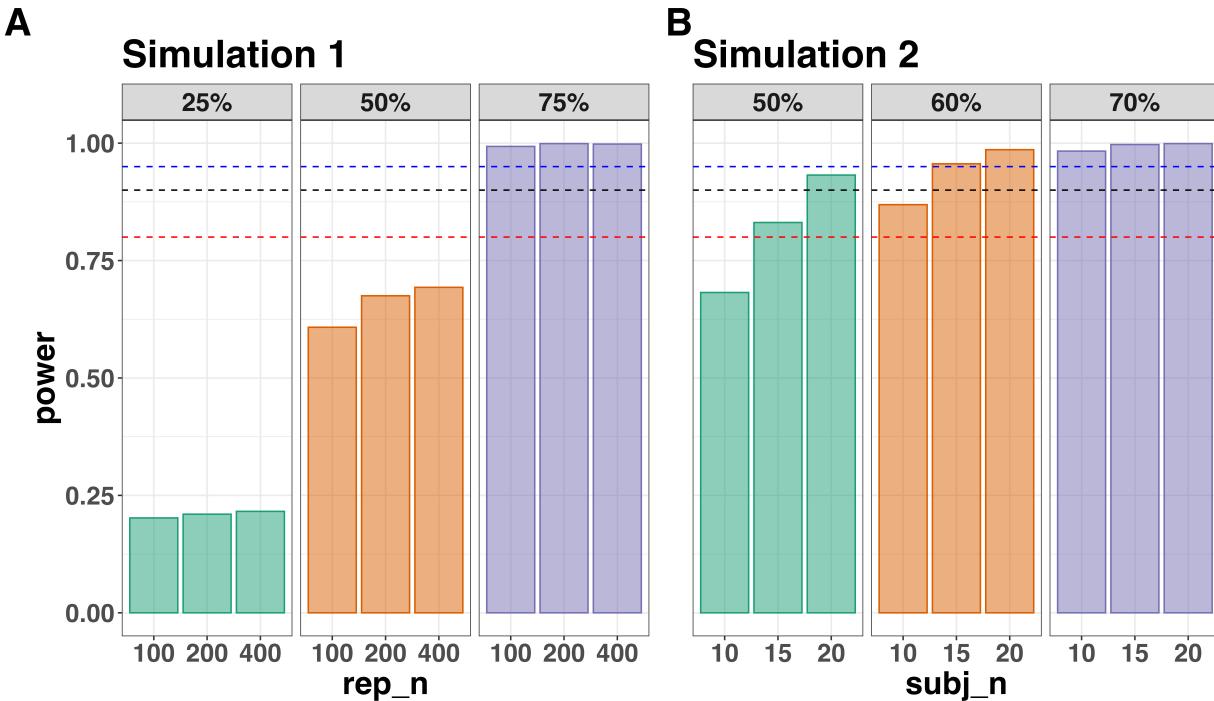


Figure 16. Statistical power across data Simulation 1 (A) and Simulation 2 (B). Power was calculated as the percentage of lower-bound 95% confidence intervals that exclude zero when the difference between prime condition is calculated (congruent - incongruent). In Simulation 1, the effect size was varied between a 25%, 50% and 75% reduction in hazard value, whereas the trial count was varied between 100, 200 and 400 trials per condition (the number of participants was fixed at N=10). In Simulation 2, the effect size was varied between a 50%, 60% and 70% reduction in hazard value, whereas the number of participants was varied between N=10, 15 and 20 (the number of trials per condition was fixed at 200). The dashed lines represent 80% (red), 90% (black) and 95% (blue) power. Abbreviations: rep_n = the number of trials per experimental condition; sub_j = the number of participants per simulated experiment.

719 **4.7.5 Planning decisions.** Now that we have summarised our simulated data,

720 what planning decisions could we make about a future study? How many trials per
721 condition should we collect and how many participants should we test? Like almost always
722 when planning future studies, the answer depends on your objectives, as well as the
723 available resources (Lakens, 2022). There is no straightforward and clear-cut answer. Some
724 considerations might be...

- 725 • How much power or precision are you looking to obtain in this particular study?
- 726 • Are you running multiple studies that have some form of replication built in?
- 727 • What resources do you have at your disposal, such as time, money and personnel?
- 728 • How easy or difficult is it to obtain the specific type of sample?

729 If we were running this kind of study in our lab, what would we do? We might pick a

730 hazard ratio of 0.4 or 0.5 as a target effect size since this is much smaller than that
731 observed in the previously published study that this work is building upon (Panis &
732 Schmidt, 2016). Then we might pick the corresponding N value (i.e., N=10 or N=15) that
733 takes you over the 80% power mark. If we wanted to maximise power based on these
734 simulations, and we had the time and resources available, then we test N=20 participants,
735 which would provide >90% power for an effect size of 0.5.

736 **But**, and this is an important “but”, unless there are unavoidable reasons, no matter

737 what planning choices we made based on these data simulations, we would not solely rely
738 on data collected from one single study. Instead, we would run a follow-up experiment that
739 replicates and extends the initial result. By doing so, we would aim to avoid the Cult of
740 the Isolated Single Study (Nelder, 1999; Tong, 2019), and thus reduce the reliance on any
741 one type of planning tool, such as a power analysis. Then, we would look for common
742 patterns across two or more experiments, rather than trying to make the case that a single
743 study on its own has sufficient evidential value to hit some criterion mark.

744

5. Discussion

745 This main motivation for writing this paper is the observation that EHA and SAT
746 analysis remain under-used in psychological research. As a consequence, the field of
747 psychological research is not taking full advantage of the many benefits EHA/SAT provides
748 compared to more conventional analyses. By providing a freely available set of tutorials,
749 which provide step-by-step guidelines and ready-to-use R code, we hope that researchers
750 will feel more comfortable using EHA/SAT in the future. Indeed, we hope that our
751 tutorials may help to overcome a barrier to entry with EHA/SAT, which is that such
752 approaches require more analytical complexity compared to mean-average comparisons.
753 While we have focused here on within-subject, factorial, small- N designs, it is important to
754 realize that EHA/SAT can be applied to other designs as well (large- N designs with only
755 one measurement per subject, between-subject designs, etc.). As such, the general workflow
756 and associated code can be modified and applied more broadly to other contexts and
757 research questions. In the following, we discuss issues relating to model complexity and
758 interpretability, individual differences, as well as limitations of the approach and future
759 extensions.

760 **5.1 What are the main use-cases of EHA for understanding cognition and brain
761 function?**

762 For those researchers, like ourselves, who are primarily interested in understanding
763 human cognitive and brain systems, we consider two broadly-defined, main use-cases of
764 EHA. First, as we hope to have made clear by this point, EHA is one way to investigating
765 a “temporal states” approach to cognitive processes. EHA provides one way to uncover
766 when cognitive states may start and stop, as well as what they may be tied to or interact
767 with. Therefore, if your research questions concern **when** and **for how long** psychological
768 states occur, our EHA tutorials could be useful tools for you to use.

769 Second, even if you are not primarily interested in studying the temporal states of
770 cognition, EHA could still be a useful tool to consider using, in order to qualify inferences
771 that are being made based on mean-average comparisons. Given that distinctly different
772 inferences can be made from the same data based on whether one computes a
773 mean-average across trials or a RT distribution of events (Figure 1), it may be important
774 for researchers to supplement mean-average comparisons with EHA. One could envisage
775 scenarios where the implicit assumption of an effect manifesting across all of the time bins
776 measured would not be supported by EHA. Therefore, the conclusion of interest would not
777 apply to all responses, but instead it would be restricted to certain aspects of time.

778 5.2 Model complexity versus interpretability

779 EHA can quickly become very complex when adding more than 1 time scale, due to
780 the many possible higher-order interactions. For example, some of the models discussed in
781 Tutorial 2a (M2) contain two time scales as covariates: the passage of time on the
782 within-trial time scale, and the passage of time on the across-trial (or within-experiment)
783 time scale. However, when trials are presented in blocks, and blocks of trials within
784 sessions, and when the experiment comprises three sessions, then four time scales can be
785 defined (within-trial, within-block, within-session, and within-experiment). From a
786 theoretical perspective, adding more than 1 time scale – and their interactions – can be
787 important to capture plasticity and other learning effects that may play out on such longer
788 time scales, and that are probably present in each experiment in general. From a practical
789 perspective, therefore, some choices need to be made to balance the amount of data that is
790 being collected per participant, condition and across the varying timescales. As one
791 example, if there are several timescales of relevance, then it might be prudent for
792 interpretational purposes to limit the number of experimental predictor variables
793 (conditions). This is of course where planning and data simulation efforts would be
794 important to provide a guide to experimental design choices (see Tutorial 4).

795 5.3 Individual differences

796 One important issue is that of possible individual differences in the overall location of
797 the distribution, and the time course of psychological effects. For example, when you wait
798 for a response of the participant on each trial, you allow the participant to have control
799 over the trial duration, and some participants might respond only when they are confident
800 that their emitted response will be correct. These issues can be avoided by introducing a
801 (relatively short) response deadline in each trial, e.g., 600 ms for simple detection tasks,
802 1000 ms for more difficult discrimination tasks, or 2 s for tasks requiring extended high-level
803 processing. Because EHA can deal in a straightforward fashion with right-censored
804 observations (i.e., trials without an observed response), introducing a response deadline is
805 recommended when designing RT experiments. Furthermore, introducing a response
806 deadline and asking participants to respond before the deadline as much as possible, will
807 also lead to individual distributions that overlap in time, which is important when selecting
808 a common analysis time window when fitting hazard and conditional accuracy models.

809 But even when using a response deadline, participants can differ qualitatively in the
810 effects they display (see Panis, 2020). One way to deal with this is to describe and
811 interpret the different patterns. Another way is to run a clustering algorithm on the
812 individual hazard estimates across all conditions. The obtained dendrogram can then be
813 used to identify a (hopefully big) cluster of participants that behave similarly, and to
814 identify a (hopefully small) cluster of participants with different behavioral patterns. One
815 might then exclude the smaller sub-group of participants before fitting a hazard model or
816 consider the possibility that different cognitive processes may be at play during task
817 performance across the different sub-groups.

818 Another approach to deal with individual differences is Bayesian prevalence (Ince,
819 Paton, Kay, & Schyns, 2021), which is a from of Small-N approach (Smith & Little, 2018).
820 This method looks at effects within each individual in the study and asks how likely it

would be to see the same result if the experiment was repeated with a new person chosen from the wider population at random. This approach allows one to quantify how typical or uncommon an observed effect is in the population, and the uncertainty around this estimate.

5.4 Limitations

Compared to the orthodox method – comparing mean-averages between conditions – the most important limitation of multi-level hazard and conditional accuracy modeling is that it might take a long time to estimate the parameters using Bayesian methods or the model might have to be simplified significantly to use frequentist methods.

Another issue is that you need a relatively large number of trials per condition to estimate the hazard function with high temporal resolution, which is required when testing predictions of process models of cognition. Indeed, in general, there is a trade-off between the number of trials per condition and the temporal resolution (i.e., bin width) of the hazard function. Therefore, we recommend researchers to collect as many trials as possible per experimental condition, given the available resources and considering the participant experience (e.g., fatigue and boredom). For instance, if the maximum session length deemed reasonable is between 1 and 2 hours, what is the maximum number of trials per condition that you could reasonably collect? After consideration, it might be worth conducting multiple testing sessions per participant and/or reducing the number of experimental conditions. Finally, there is a user-friendly online tool for calculating statistical power as a function of the number of trials as well as the number of participants, and this might be worth consulting to guide the research design process (Baker et al., 2021).

We did not discuss continuous-time EHA, nor continuous-time SAT analysis. As indicated by Allison (2010), learning discrete-time EHA methods first will help in learning continuous-time methods. Given that RT is typically treated as a continuous variable, it is

possible that continuous-time methods will ultimately prevail. However, they require much more data to estimate the continuous-time hazard (rate) function well. Thus, by trading a bit of temporal resolution for a lower number of trials, discrete-time methods seem ideal for dealing with typical psychological time-to-event data sets for which there are less than ~200 trials per condition per experiment.

5.5 Extensions

The hazard models in this tutorial assume that there is one event of interest. For RT data, this event constitutes a single transition between an “idle” state and a “responded” state. However, in certain situations, more than one event of interest might exist. For example, in a medical or health-related context, an individual might transition back and forth between a “healthy” state and a “depressed” state, before being absorbed into a final “death” state. When you have data on the timing of these transitions, one can apply multi-state hazard models, which generalize EHA to transitions between three or more states (Steele, Goldstein, & Browne, 2004). Also, the predictor variables in this tutorial are time-invariant, i.e., their value did not change over the course of a trial. Thus, another extension is to include time-varying predictors, i.e., predictors whose value can change across the time bins within a trial (Allison, 2010). For example, when gaze position is tracked during a visual search trial, the gaze-target distance will vary during a trial when the eyes move around before a manual response is given; shorter gaze-target distances should be associated with a higher hazard of response occurrence. Note that the effect of a time-varying predictor (e.g., an occipital EEG signal) can itself vary over time.

6. Conclusions

Estimating the temporal distributions of RT and accuracy provide a rich source of information on the time course of cognitive processing, which have been largely undervalued in the history of experimental psychology and cognitive neuroscience.

871 Statistically controlling for the passage of time during data analysis is equally important as
872 experimental control during the design of an experiment, to better understand human
873 behavior in experimental paradigms. We hope that by providing a set of hands-on,
874 step-by-step tutorials, which come with custom-built and freely available code, researchers
875 will feel more comfortable embracing EHA and investigating the temporal profile of
876 cognitive states. On a broader level, we think that wider adoption of such approaches will
877 have a meaningful impact on the inferences drawn from data, as well as the development of
878 theories regarding the structure of cognition.

879

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1075

Supplementary material

1076 **A. Definitions of discrete-time hazard, survivor, probability mass, and**
 1077 **conditional accuracy functions**

1078 The shape of a distribution of waiting times can be described in multiple ways (Luce,
 1079 1991). After dividing time in discrete, contiguous time bins indexed by t , let RT be a
 1080 discrete random variable denoting the rank of the time bin in which a particular person's
 1081 response occurs in a particular experimental condition. Because waiting times can only
 1082 increase, discrete-time EHA focuses on the discrete-time hazard function

$$1083 \quad h(t) = P(RT = t | RT \geq t) \quad (1)$$

1084 and the discrete-time survivor function

$$1085 \quad S(t) = P(RT > t) = [1-h(t)].[1-h(t-1)].[1-h(t-2)] \dots [1-h(1)] \quad (2)$$

1086 and not on the probability mass function

$$1087 \quad P(t) = P(RT = t) = h(t).S(t-1) \quad (3)$$

1088 nor the cumulative distribution function

$$1089 \quad F(t) = P(RT \leq t) = 1-S(t) \quad (4)$$

1090 The discrete-time hazard function of event occurrence gives you for each bin the
 1091 probability that the event occurs (sometime) in that bin, given that the event has not
 1092 occurred yet in previous bins. This conditionality in the definition of hazard is what makes
 1093 the hazard function so diagnostic for studying event occurrence, as an event can physically
 1094 not occur when it has already occurred before. While the discrete-time hazard function
 1095 assesses the unique risk of event occurrence associated with each time bin, the
 1096 discrete-time survivor function cumulates the bin-by-bin risks of event *non*occurrence to
 1097 obtain the probability that the event occurs after bin t . The probability mass function
 1098 cumulates the risk of event occurrence in bin t with the risks of event nonoccurrence in

1099 bins 1 to t-1. From equation 3 we find that hazard in bin t is equal to $P(t)/S(t-1)$.

1100 For two-choice RT data, the discrete-time hazard function can be extended with the
 1101 discrete-time conditional accuracy function

$$1102 \quad ca(t) = P(\text{correct} \mid RT = t) \quad (5)$$

1103 which gives you for each bin the probability that a response is correct given that it is
 1104 emitted in time bin t (Allison, 2010; Kantowitz & Pachella, 2021; Wickelgren, 1977). This
 1105 latter function is also known as the micro-level speed-accuracy tradeoff (SAT) function.

1106 The survivor function provides a context for the hazard function, as $S(t-1) = P(RT >$
 1107 $t-1) = P(RT \geq t)$ tells you on how many percent of the trials the estimate $h(t) = P(RT =$
 1108 $t \mid RT \geq t)$ is based. The probability mass function provides a context for the conditional
 1109 accuracy function, as $P(t) = P(RT = t)$ tells you on how many percent of the trials the
 1110 estimate $ca(t) = P(\text{correct} \mid RT = t)$ is based.

1111 While psychological RT data is typically measured in small, continuous units (e.g.,
 1112 milliseconds), discrete-time EHA treats the RT data as interval-censored data, because it
 1113 only uses the information that the response occurred sometime in a particular bin of time
 1114 $(x,y]: x < RT \leq y$. If we want to use the exact event times, then we treat time as a
 1115 continuous variable, and let RT be a continuous random variable denoting a particular
 1116 person's response time in a particular experimental condition. Continuous-time EHA does
 1117 not focus on the cumulative distribution function $F(t) = P(RT \leq t)$ and its derivative, the
 1118 probability density function $f(t) = F(t)'$, but on the survivor function $S(t) = P(RT > t)$
 1119 and the hazard rate function $\lambda(t) = f(t)/S(t)$. The hazard rate function gives you the
 1120 instantaneous *rate* of event occurrence at time point t, given that the event has not
 1121 occurred yet.

1122 **B. Custom functions for descriptive discrete-time hazard analysis**

1123 We defined 12 custom functions that we list here.

- 1124 • censor(df,timeout,bin_width) : divide the time segment $(0, \text{timeout}]$ in bins, identify
1125 any right-censored observations, and determine the discrete RT (time bin rank)
- 1126 • ptb(df) : transform the person-trial data set to the person-trial-bin data set
- 1127 • setup_lt(ptb) : set up a life table for each level of 1 independent variable
- 1128 • setup_lt_2IV(ptb) : set up a life table for each combination of levels of 2
1129 independent variables
- 1130 • calc_ca(df) : estimate the conditinal accuracies when there is 1 independent variable
- 1131 • calc_ca_2IV(df) : estimate the conditional accuracies when there are 2 independent
1132 variables
- 1133 • join_lt_ca(df1,df2) : add the $\text{ca}(t)$ estimates to the life tables (1 independent
variable)
- 1134 • join_lt_ca_2IV(df1, df2) : add the $\text{ca}(t)$ estimates to the life tables (2 independent
variables)
- 1135 • extract_median(df) : estimate quantiles $S(t)._{50}$ (1 independent variable)
- 1136 • extract_median_2IV(df) : estimate quantiles $S(t)._{50}$ (2 independent variables)
- 1137 • plot_eha(df, subj, haz_yaxis=1, first_bin_shown=1, aggregated_data=F, Nsubj=6)
1138 : create plots of the discrete-time functions (1 independent variable), and specify the
1139 upper limit of the y-axis in the hazard plot, with which bin to start plotting, whether
1140 the data is aggregated across participants, and across how many participants
- 1141 • plot_eha_2IV(df, subj, haz_yaxis=1, first_bin_shown=1, aggregated_data=F,
1142 Nsubj=6) : create plots of the discrete-time functions (2 independent variables), and
1143 specify the upper limit of the y-axis in the hazard plot, with which bin to start
1144 plotting, whether the data is aggregated across participants, and across how many
1145 participants
- 1146
- 1147

1148 When you want to analyse simple RT data from a detection experiment with one
1149 independent variable, the functions calc_ca() and join_lt_ca() should not be used, and
1150 the code to plot the conditional accuracy functions should be removed from the function

1151 plot_eha(). When you want to analyse simple RT data from a detection experiment with
1152 two independent variables, the functions calc_ca_2IV() and join_lt_ca_2IV() should not
1153 be used, and the code to plot the conditional accuracy functions should be removed from
1154 the function plot_eha_2IV().

1155 **C. Link functions**

1156 Popular link functions include the logit link and the complementary log-log link, as
1157 shown in Figure 15.

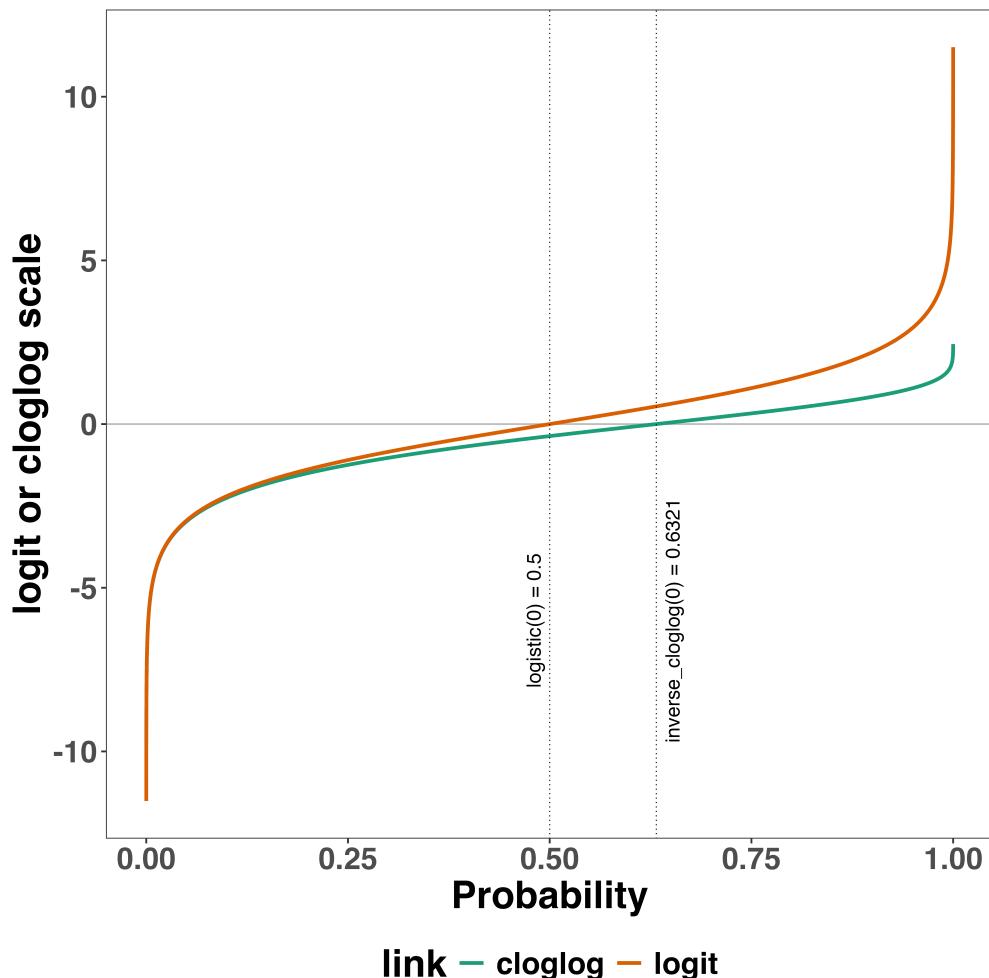


Figure 17. The logit and cloglog link functions.

₁₁₅₈ **D. Regression equations**

₁₁₅₉ An example (single-level) discrete-time hazard model with three predictors (TIME,
₁₁₆₀ X₁, X₂), the cloglog link function, and a second-order polynomial specification for TIME
₁₁₆₁ can be written as follows:

$$\begin{aligned} \text{cloglog}[h(t)] &= \ln(-\ln[1-h(t)]) = [\beta_0 \text{ONE} + \beta_1(\text{TIME}-9) + \beta_2(\text{TIME}-9)^2] + [\beta_3 X_1 + \beta_4 X_2 \\ &\quad + \beta_5 X_2(\text{TIME}-9)] \end{aligned} \quad (6)$$

₁₁₆₂ The main predictor variable TIME is the time bin index t that is centered on value 9
₁₁₆₃ in this example. The first set of terms within brackets, the parameters β_0 to β_2 multiplied
₁₁₆₄ by their polynomial specifications of (centered) time, represents the shape of the baseline
₁₁₆₅ cloglog-hazard function (i.e., when all predictors X_i take on a value of zero). The second
₁₁₆₆ set of terms (the beta parameters β_3 to β_5) represents the vertical shift in the baseline
₁₁₆₇ cloglog-hazard for a 1 unit increase in the respective predictor variable. Predictors can be
₁₁₆₈ discrete, continuous, and time-varying or time-invariant. For example, the effect of a 1 unit
₁₁₆₉ increase in X₁ is to vertically shift the whole baseline cloglog-hazard function by β_3
₁₁₇₀ cloglog-hazard units. However, if the predictor interacts linearly with TIME (see X₂ in the
₁₁₇₁ example), then the effect of a 1 unit increase in X₂ is to vertically shift the predicted
₁₁₇₂ cloglog-hazard in bin 9 by β_4 cloglog-hazard units (when TIME-9 = 0), in bin 10 by $\beta_4 +$
₁₁₇₃ β_5 cloglog-hazard units (when TIME-9 = 1), and so forth. To interpret the effects of a
₁₁₇₄ predictor, its β parameter is exponentiated, resulting in a hazard ratio (due to the use of
₁₁₇₅ the cloglog link). When using the logit link, exponentiating a β parameter results in an
₁₁₇₆ odds ratio.

₁₁₇₇ An example (single-level) discrete-time hazard model with a general specification for
₁₁₇₈ TIME (separate intercepts for each of six bins, where D1 to D6 are binary variables
₁₁₇₉ identifying each bin) and a single predictor (X₁) can be written as follows:

$$\text{cloglog}[h(t)] = [\beta_0 D1 + \beta_1 D2 + \beta_2 D3 + \beta_3 D4 + \beta_4 D5 + \beta_5 D6] + [\beta_6 X_1] \quad (7)$$

E. Prior distributions

To gain a sense of what prior *logit* values would approximate a uniform distribution on the probability scale, Kurz (2023a) simulated a large number of draws from the Uniform(0,1) distribution, converted those draws to the log-odds metric, and fitted a Student's t distribution. Row C in Figure 16 shows that using a t-distribution with 7.61 degrees of freedom and a scale parameter of 1.57 as a prior on the logit scale, approximates a uniform distribution on the probability scale. According to Kurz (2023a), such a prior might be a good prior for the intercept(s) in a logit-hazard model, while the N(0,1) prior in row D might be a good prior for the non-intercept parameters in a logit-hazard model, as it gently regularizes p towards .5 (i.e., a zero effect on the logit scale).

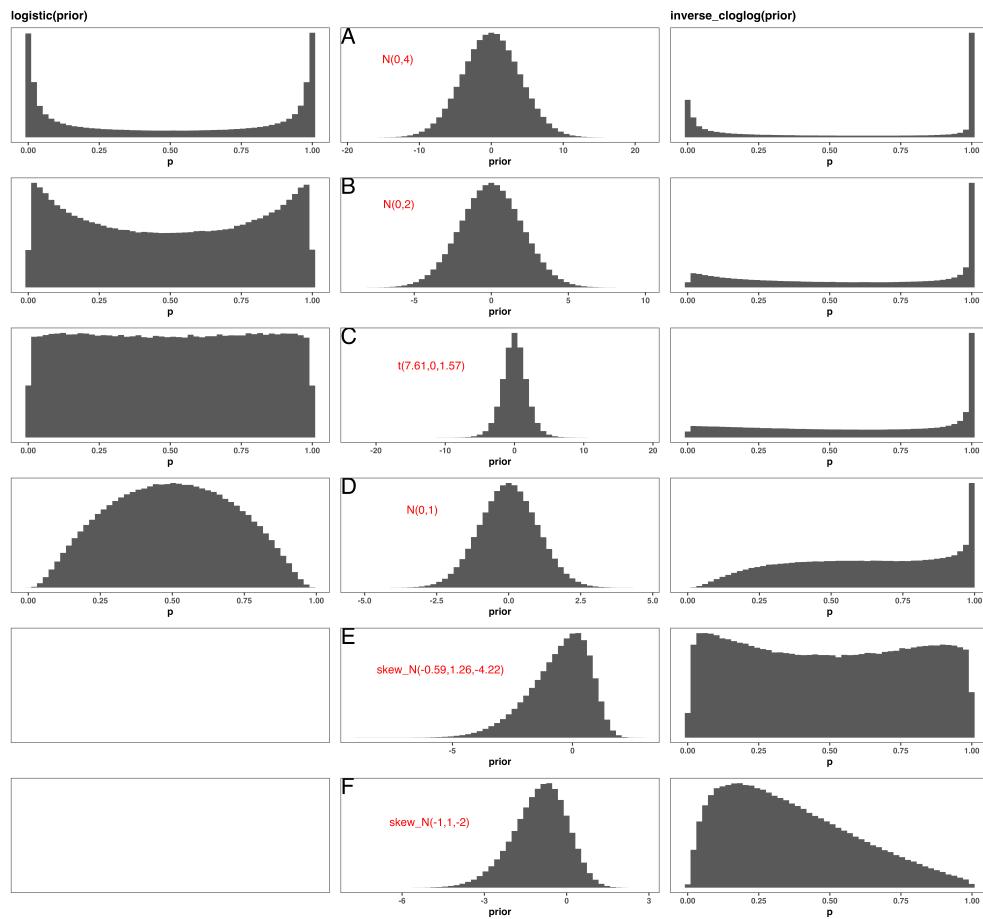


Figure 18. Prior distributions for the Intercept on the logit and/or cloglog scales (middle column), and their implications on the probability scale after applying the inverse-logit (or logistic) transformation (left column), and the inverse-cloglog transformation (right column).

1193 To gain a sense of what prior *cloglog* values would approximate a uniform distribution
 1194 on the hazard probability scale, we followed Kurz's approach and simulated a large number
 1195 of draws from the Uniform(0,1) distribution, converted them to the cloglog metric, and
 1196 fitted a skew-normal model (due to the asymmetry of the cloglog link function). Row E
 1197 shows that using a skew-normal distribution with a mean of -0.59, a standard deviation of
 1198 1.26, and a skewness of -4.22 as a prior on the cloglog scale, approximates a uniform
 1199 distribution on the probability scale. However, because hazard values below .5 are more
 1200 likely in RT studies, using a skew-normal distribution with a mean of -1, a standard

1201 deviation of 1, and a skewness of -2 as a prior on the cloglog scale (row F), might be a good
1202 weakly informative prior for the intercept(s) in a cloglog-hazard model.

1203 **F. Advantages of hazard analysis**

1204 Statisticians and mathematical psychologists recommend focusing on the hazard
1205 function when analyzing time-to-event data for various reasons. First, as discussed by
1206 Holden, Van Orden, and Turvey (2009), “probability density [and mass] functions can
1207 appear nearly identical, both statistically and to the naked eye, and yet are clearly different
1208 on the basis of their hazard functions (but not vice versa). Hazard functions are thus more
1209 diagnostic than density functions” (p. 331) when one is interested in studying the detailed
1210 shape of a RT distribution (see also Figure 1 in Panis, Schmidt, et al., 2020). Therefore,
1211 when the goal is to study how psychological effects change over time, hazard and
1212 conditional accuracy functions are the preferred ways to describe the RT + accuracy data.

1213 Second, because RT distributions may differ from one another in multiple ways,
1214 Townsend (1990) developed a dominance hierarchy of statistical differences between two
1215 arbitrary distributions A and B. For example, if $h_A(t) > h_B(t)$ for all t, then both hazard
1216 functions are said to show a complete ordering. Townsend (1990) concluded that stronger
1217 conclusions can be drawn from data when comparing the hazard functions using EHA. For
1218 example, when mean A < mean B, the hazard functions might show a complete ordering
1219 (i.e., for all t), a partial ordering (e.g., only for $t > 300$ ms, or only for $t < 500$ ms), or they
1220 may cross each other one or more times.

1221 Third, EHA does not discard right-censored observations when estimating hazard
1222 functions, that is, trials for which we do not observe a response during the data collection
1223 period in a trial so that we only know that the RT must be larger than some value (e.g.,
1224 the response deadline). This is important because although a few right-censored
1225 observations are inevitable in most RT tasks, a lot of right-censored observations are

expected in experiments on masking, the attentional blink, and so forth. In other words, by using EHA you can analyze RT data from experiments that typically do not measure response times. As a result, EHA can also deal with long RTs in experiments without a response deadline, which are typically treated as outliers and are discarded before calculating a mean. This orthodox procedure leads to underestimation of the true mean. By introducing a fixed censoring time for all trials at the end of the analysis time window, trials with long RTs are not discarded but contribute to the risk set of each bin.

Fourth, hazard modeling allows incorporating time-varying explanatory covariates such as heart rate, electroencephalogram (EEG) signal amplitude, gaze location, etc. (Allison, 2010). This is useful for linking physiological effects to behavioral effects when performing cognitive psychophysiology (Meyer et al., 1988).

Finally, as explained by Kelso, Dumas, and Tognoli (2013), it is crucial to first have a precise description of the macroscopic behavior of a system (here: $h(t)$ and possibly $ca(t)$ functions) in order to know what to derive on the microscopic level. EHA can thus solve the problem of model mimicry, i.e., the fact that different computational models can often predict the same mean RTs as observed in the empirical data, but not necessarily the detailed shapes of the empirical RT hazard distributions. Also, fitting parametric functions or computational models to data without studying the shape of the empirical discrete-time $h(t)$ and $ca(t)$ functions can miss important features in the data (Panis, Moran, et al., 2020; Panis & Schmidt, 2016).