

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

3 Sven Panis¹ & Richard Ramsey¹

4 ¹ ETH Zürich

5 Author Note

6 Neural Control of Movement lab, Department of Health Sciences and Technology
7 (D-HEST). Social Brain Sciences lab, Department of Humanities, Social and Political
8 Sciences (D-GESS).

9 The authors made the following contributions. Sven Panis: Conceptualization,
10 Writing - Original Draft Preparation, Writing - Review & Editing; Richard Ramsey:
11 Conceptualization, Writing - Review & Editing, Supervision.

12 Correspondence concerning this article should be addressed to Sven Panis, ETH
13 GLC, room G16.2, Gloriastrasse 37/39, 8006 Zürich. E-mail: sven.panis@hest.ethz.ch

14

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 reaction 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.

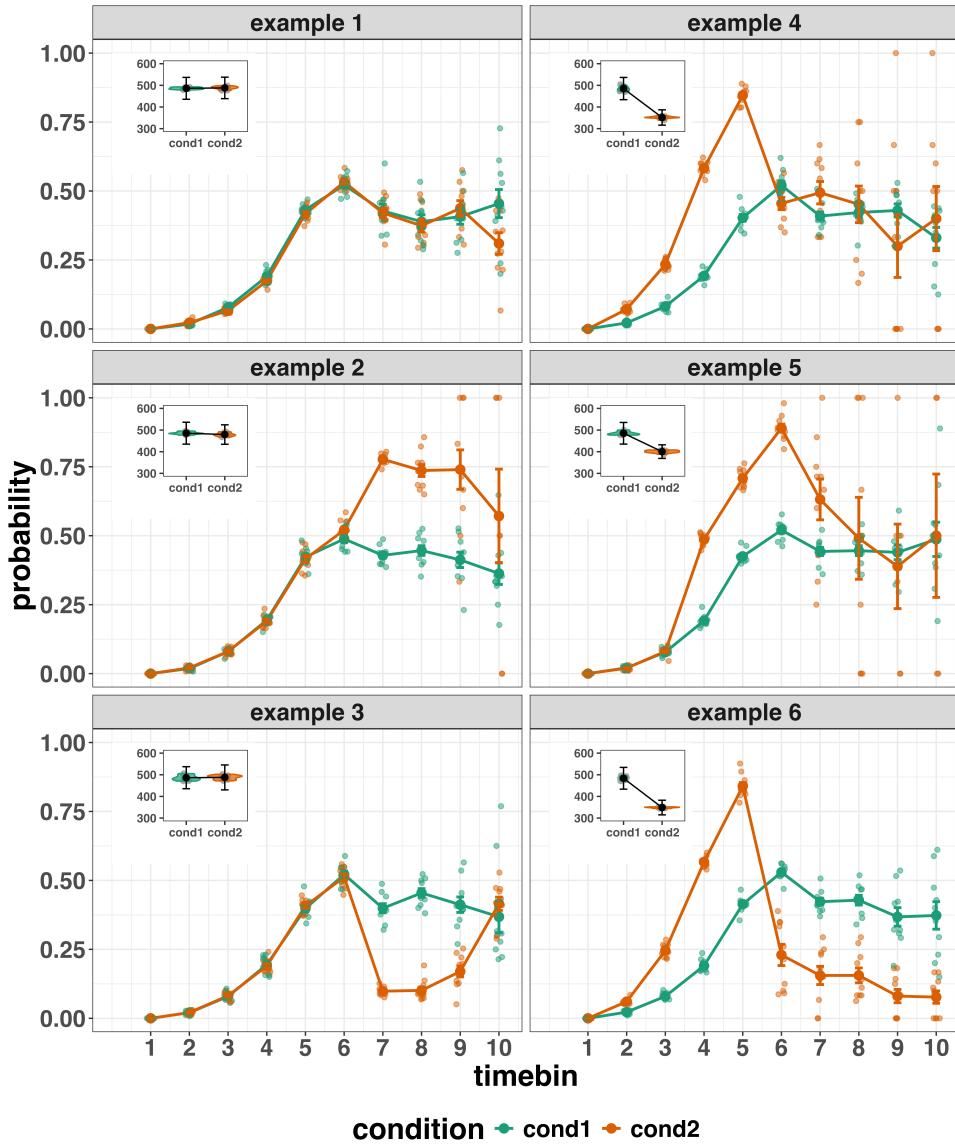


Figure 1. Means versus distributional shapes for six different simulated data set examples.

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 reaction 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., Makeham, William M., 1860). The same logic
83 has been applied to psychological time-to-event data, as previously demonstrated (Panis,
84 Schmidt, et al., 2020). Here, in the current paper, we focus on a distributional method for
85 time-to-event data known as discrete-time Event History Analysis (EHA), a.k.a. survival
86 analysis, hazard analysis, duration analysis, failure-time analysis, and transition analysis
87 (Singer & Willett, 2003). We hope to show the value of EHA for knowledge and theory
88 building in cognitive psychology and related areas of research, such as cognitive
89 neuroscience. Moreover, we provide tutorials that provide step-by-step code and
90 instructions in the hope that we can enable others to use EHA in a more routine, efficient
91 and effective manner.

92 1.2 Aims and structure of the paper

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

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

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

115 In Tutorial 2a, we illustrate how one can fit Bayesian multi-level regression models to
116 RT data using the R package `brms`. We discuss possible link functions, and plot the
117 model-based effects of our predictors of interest. In Tutorial 2b we fit Bayesian multi-level

regression models to *timed* accuracy data to perform a micro-level speed-accuracy tradeoff (SAT) analysis, which complements the EHA of RT data for choice RT data. In Tutorial 3a, we illustrate how to fit the same type of multilevel regression model for RT data in a frequentist framework using the R package lme4. We then briefly compare and contrast these inferential frameworks when applied to EHA. In Tutorial 3b, we illustrate how to perform the SAT analysis in a frequentist framework.

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

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

¹⁴³ Hill, & Vehtari, 2020; Winter, 2019). Our focus here is not on providing a detailed account
¹⁴⁴ of the underlying regression equations, since this topic has been comprehensively covered
¹⁴⁵ many times before. Instead, we want to provide an intuition regarding how EHA works in
¹⁴⁶ general, as well as in the context of experimental psychology. As such, we only supply
¹⁴⁷ regression equations in the supplementary material.

¹⁴⁸ **2.1 Basic features of event history analysis**

¹⁴⁹ To apply EHA, one must be able to:

- ¹⁵⁰ 1. define an event of interest that represents a qualitative change that can be situated in
¹⁵¹ time (e.g., a button press, a saccade onset, a fixation offset, etc.);
- ¹⁵² 2. define time point zero (e.g., target stimulus onset, fixation onset);
- ¹⁵³ 3. measure the passage of time between time point zero and event occurrence in discrete
¹⁵⁴ or continuous time units.

¹⁵⁵ In EHA, the definition of hazard and the type of models employed depend on
¹⁵⁶ whether one is using continuous or discrete time units. Since our focus here is on hazard
¹⁵⁷ models that use discrete time units, we describe that approach. After dividing time in
¹⁵⁸ discrete, contiguous time bins indexed by t (e.g., $t = 1:10$ timebins), let RT be a discrete
¹⁵⁹ random variable denoting the rank of the time bin in which a particular person's response
¹⁶⁰ occurs in a particular experimental condition. For example, the first response might occur
¹⁶¹ at 546 ms and it would be in timebin 6 (any RTs from 501 ms to 600 ms).

¹⁶² Discrete-time EHA focuses on the discrete-time hazard function of event occurrence
¹⁶³ and the discrete-time survivor function (Figure 2). The equations that define both of these
¹⁶⁴ functions are reported in part A of the supplementary material. The discrete-time hazard
¹⁶⁵ function gives you, for each time bin, the probability that the event occurs (sometime) in

¹⁶⁶ bin t, given that the event does not occur in previous bins. In other words, it reflects the
¹⁶⁷ instantaneous likelihood that the event occurs in the current bin, given that it has not yet
¹⁶⁸ occurred in the past, i.e., in one of the prior bins. In contrast, the discrete-time survivor
¹⁶⁹ function cumulates the bin-by-bin risks of event *nonoccurrence* to obtain the survival
¹⁷⁰ probability, the probability that the event occurs after bin t. In other words, the survivor
¹⁷¹ function gives you for each time bin the likelihood that the event occurs in the future, i.e.,
¹⁷² in one of the subsequent timebins.

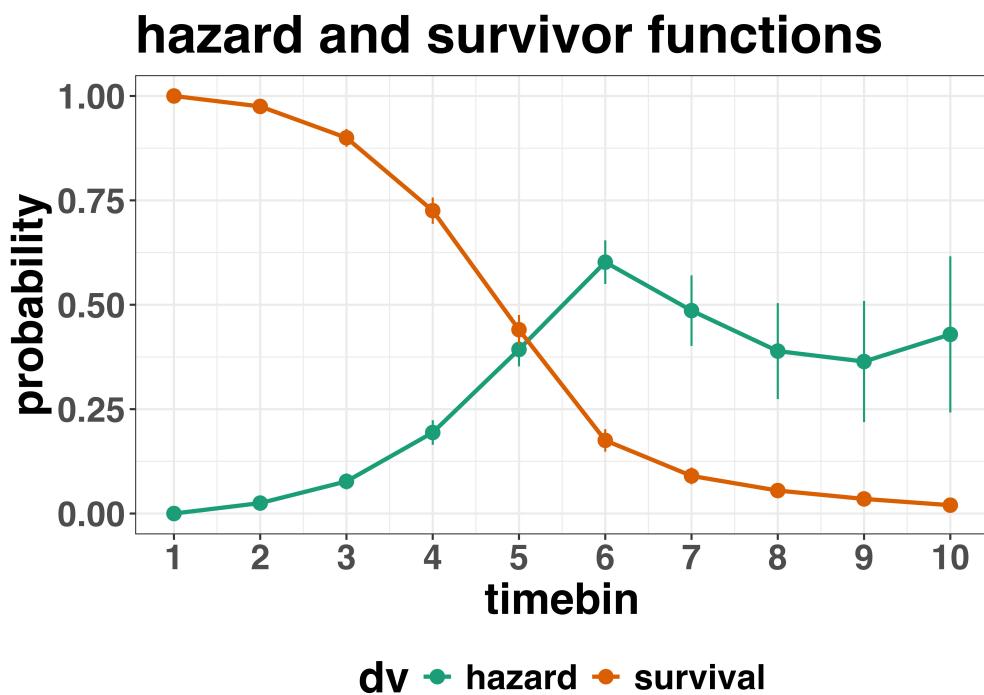


Figure 2. Discrete-time hazard and survivor functions. Discrete time-to-event data were simulated for 200 trials of 1 experimental condition. While the hazard function is the vehicle for inferring the time course of cognitive processes, the survival probability $S(t-1)$ can help to qualify or provide 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 $S(t-1=5) = .44$. 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.

173 2.2 Benefits of event history analysis

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

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

197 2.3 Event history analysis in the context of experimental psychology

198 To make EHA more relevant to researchers studying cognitive psychology and
199 cognitive neuroscience, in this section we provide a relevant worked example and consider
200 implications that are relevant to that domain of research.

201 **2.3.1 A worked example.** In the context of experimental psychology, it is
202 common for participants to be presented with either a 1-button detection task or a
203 2-button discrimination task. For example, a task may involve choosing between two
204 response options with only one of them being correct. For such two-choice RT data, the
205 discrete-time EHA of the RT data (hazard and survivor functions) can be extended with a
206 discrete-time SAT analysis of the timed accuracy data. Specifically, the hazard function of
207 event occurrence can be extended with the discrete-time conditional accuracy function,
208 which gives you the probability that a response is correct given that it is emitted in time
209 bin t (Allison, 2010; Kantowitz & Pachella, 2021; Wickelgren, 1977). We refer to this
210 extended (hazard + conditional accuracy) analysis for choice RT data as EHA/SAT.

211 Integrating results between hazard and conditional accuracy functions for choice RT
212 data can be informative for understanding psychological processes. To illustrate, we
213 consider a hypothetical choice RT example that is inspired by real data (Panis & Schmidt,
214 2016), but simplified to make the main point clearer (Figure 3). In a standard priming
215 paradigm, there is a prime stimulus (e.g., an arrow pointing left or right) followed by a
216 target stimulus (another arrow pointing left or right). The prime can then be congruent or
217 incongruent with the target.

218 Figure 3 shows that the early upswing in hazard is equal for both priming conditions,
219 and that early responses are always correct in the congruent condition and always incorrect
220 in the incongruent condition. These results show that for short waiting times (< bin 6),
221 responses always follow the prime (and not the target, as instructed). Between 500 and 600
222 ms the target-triggered response channel is activated and causes response competition –

223 ca(6) = .5 – and a lower hazard probability in the incongruent condition. For waiting times
224 of 600 ms or more, the hazard of response occurrence is lower in incongruent compared to
225 congruent trials, and all responses emitted in these later bins are correct.

226 This joint pattern of results is interesting because it can provide meaningfully
227 different conclusions about psychological processes compared to conventional analyses, such
228 as computing mean-average RT across trials. Mean-average RT would only represent the
229 overall ability of cognition to overcome interference, on average, across trials. For instance,
230 if mean-average RT was higher in incongruent than congruent trials, one may conclude
231 that cognitive mechanisms that support interference control are working as expected across
232 trials, and are indexed by each recorded response. But such a conclusion is not supported
233 when the effects are explored over a timeline. Instead, the psychological conclusion is much
234 more nuanced and suggests that multiple states start, stop and possibly interact over a
235 particular temporal window.

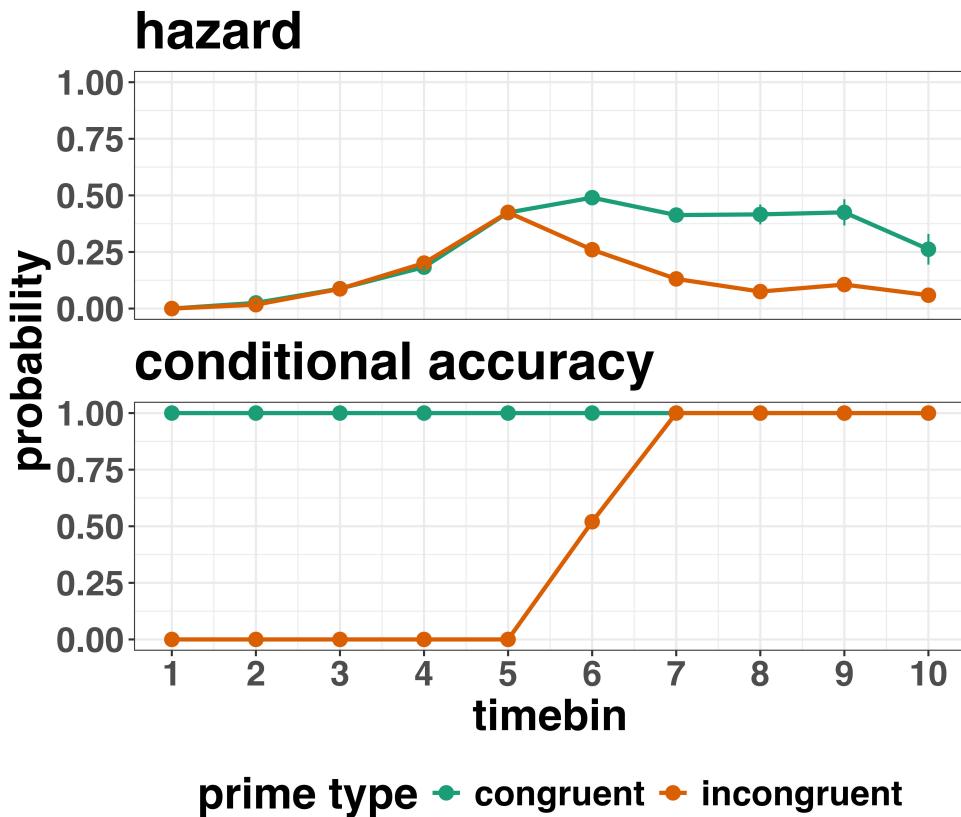


Figure 3. Discrete-time hazard and conditional accuracy functions. Discrete time-to-event and conditional accuracy data were simulated for 2000 trials for each of two priming conditions (congruent and incongruent prime stimuli).

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

245 **2.3.2 Implications for designing experiments.** Performing EHA in
246 experimental psychology has implications for how experiments are designed. Indeed, if
247 trials are categorised as a function of when responses occur, then each timebin will only
248 include a subset of the total number of trials. For example, let's consider an experiment
249 where each participant performs 2 conditions and there are 100 trial repetitions per
250 condition. Those 100 trials must be distributed in some manner across the chosen number
251 of bins.

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

260 In contrast to the large- N design that typically average across many participants
261 without being able to scrutinize individual data patterns, small- N designs retain crucial
262 information about the data patterns of individual observers. This can be advantageous
263 whenever participants differ systematically in their strategies or in the time courses of their
264 effects, so that averaging them would lead to misleading data patterns. Note that because
265 statistical power derives both from the number of participants and from the number of
266 repeated measures per participant and condition, small- N designs can still achieve what
267 are generally considered acceptable levels of statistical power, if they have a sufficient
268 amount of data overall (Baker et al., 2021; Smith & Little, 2018).

269 3. An overview of the general analytical workflow

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

273 3.1 Data science workflow and descriptive statistics

274 Descriptive, data science workflow. We perform data wrangling following tidyverse
275 principles and a functional programming approach (Wickham, Çetinkaya-Rundel, &
276 Grolemund, 2023). Functional programming basically means you don't write your own
277 loops but instead use functions that have been built and tested by others. [[more here, as
278 necessary]].

279 3.2 Inferential statistical approach

280 Our lab adopts a estimation approach to multi-level regression (Kruschke & Liddell,
281 2018; Winter, 2019), which is heavily influenced by the Bayesian framework as suggested
282 by Richard McElreath (Kurz, 2023b; McElreath, 2018). We also use a “keep it maximal”
283 approach to specifying varying (or random) effects (Barr, Levy, Scheepers, & Tily, 2013).
284 This means that wherever possible we include varying intercepts and slopes per participant
285 To make inferences, we use two main approaches. We compare models of different
286 complexity, using information criteria (e.g., WAIC) and cross-validation (e.g., LOO), to
287 evaluate out-of-sample predictive accuracy (McElreath, 2018). We also take the most
288 complex model and evaluate key parameters of interest using point and interval estimates.

²⁸⁹ **3.3 Implementation**

²⁹⁰ We used R (Version 4.4.0; R Core Team, 2024)¹ for all reported analyses. The
²⁹¹ content of the tutorials, in terms of EHA and multi-level regression modelling, is mainly
²⁹² based on Allison (2010), Singer and Willett (2003), McElreath (2018), Kurz (2023a), and
²⁹³ Kurz (2023b).

²⁹⁴ **4. Tutorials**

²⁹⁵ Tutorials 1a and 1b show how to calculate and plot the descriptive statistics of
²⁹⁶ EHA/SAT when there are one and two independent variables, respectively. Tutorials 2a
²⁹⁷ and 2b illustrate how to use Bayesian multilevel modeling to fit hazard and conditional
²⁹⁸ accuracy models, respectively. Tutorials 3a and 3b show how to implement, respectively,
²⁹⁹ multilevel models for hazard and conditional accuracy in the frequentist framework.
³⁰⁰ Additionally, to further simplify the process for other users, the tutorials rely on a set of
³⁰¹ our own custom functions that make sub-processes easier to automate, such as data
³⁰² wrangling and plotting functions (see part B in the supplemental material for a list of the

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, & Broder, 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), *tidyverse* (Version 2.0.0; Wickham et al., 2019), and *tinylabels* (Version 0.2.4; Barth, 2023).

303 custom functions).

304 Our list of tutorials is as follows:

- 305 • 1a. Wrangle raw data and calculate descriptive stats for one independent variable.
- 306 • 1b. Wrangle raw data and calculate descriptive stats for two independent variables.
- 307 • 2a. Bayesian multilevel modeling for $h(t)$
- 308 • 2b. Bayesian multilevel modeling for $ca(t)$
- 309 • 3a. Frequentist multilevel modeling for $h(t)$
- 310 • 3b. Frequentist multilevel modeling for $ca(t)$

311 Planning (T4) - if we get a simulation and power analysis script working, which we
312 are happy with then we could include it here.

313 **4.1 Tutorial 1a: Calculating descriptive statistics using a life table**

314 **4.1.1 Data wrangling aims.** Our data wrangling procedures serve two related
315 purposes. First, we want to summarise and visualise descriptive statistics that relate to our
316 main research questions about the time course of psychological processes. Second, we want
317 to produce two different data sets that can each be submitted to different types of
318 inferential modelling approaches. The two types of data structure we label as ‘person-trial’
319 data and ‘person-trial-bin’ data. The ‘person-trial’ data (Table 1) will be familiar to most
320 researchers who record behavioural responses from participants, as it represents the
321 measured RT and accuracy per trial within an experiment. This data set is used when
322 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.

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

332 **4.1.2 A real data wrangling example.** To illustrate how to quickly set up life
 333 tables for calculating the descriptive statistics (functions of discrete time), we use a
 334 published data set on masked response priming from Panis and Schmidt (2016). In their
 335 first experiment, Panis and Schmidt (2016) presented a double arrow for 94 ms that
 336 pointed left or right as the target stimulus with an onset at time point zero in each trial.
 337 Participants had to indicate the direction in which the double arrow pointed using their
 338 corresponding index finger, within 800 ms after target onset. Response time and accuracy
 339 were recorded on each trial. Prime type (blank, congruent, incongruent) and mask type
 340 were manipulated. Here we focus on the subset of trials in which no mask was presented.

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

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

347 The required column names are as follows:

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

354 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")))

```

355 Next, we can set up the life tables and plots of the discrete-time functions $h(t)$, $S(t)$,
 356 $ca(t)$, and $P(t)$ – see part A of the supplementary material for their definitions. To do so
 357 using a functional programming approach, one has to nest the data within participants
 358 using the group_nest() function, and supply a user-defined censoring time and bin width
 359 to our custom function “censor()”, as follows.

```

data_nested <- data_wr %>% group_nest(pid)

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

```

360 Note that the censoring time should be a multiple of the bin width (both in ms). The

361 censoring time should be a time point after which no informative responses are expected

362 anymore. In experiments that implement a response deadline in each trial the censoring

363 time can equal that deadline time point. Trials with a RT larger than the censoring time,

364 or trials in which no response is emitted during the data collection period, are treated as

365 right-censored observations in EHA. In other words, these trials are not discarded, because

366 they contain the information that the event did not occur before the censoring time.

367 Removing such trials before calculating the mean event time will result in underestimation

368 of the true mean.

369 The person-trial-bin oriented data set is created by our custom function ptb(), and it

370 has one row for each time bin (of each trial) that is at risk for event occurrence. The

371 variable “event” in the person-trial-bin oriented data set indicates whether a response

372 occurs (1) or not (0) for each bin.

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

374 calculate the conditional accuracies using our custom function calc_ca(), add the ca(t)

375 estimates to the life table using our custom function join_lt_ca(), and then plot the

376 descriptive statistics using our custom function plot_eha(). When creating the plots, some

377 warning messages will likely be generated, like these:

- Removed 2 rows containing missing values or values outside the scale range

379 (geom_line()).

- 380 • Removed 2 rows containing missing values or values outside the scale range
381 (`geom_point()`).
- 382 • Removed 2 rows containing missing values or values outside the scale range
383 (`geom_segment()`).

384 The warning messages are generated because some bins have no hazard and $ca(t)$
385 estimates, and no error bars. They can thus safely be ignored. One can now inspect
386 different aspects, including the life table for a particular condition of a particular subject,
387 and a plot of the different functions for a particular participant.

388 In general, it is important to visually inspect the functions first for each participant,
389 in order to identify individuals that may be guessing (e.g., a flat conditional accuracy
390 function at .5 indicates that someone may be guessing), outlying individuals, and/or
391 different groups with qualitatively different behavior.

392 Table 3 shows the life table for condition “blank” (no prime stimulus presented) for
393 participant 6. A life table includes for each time bin, the risk set (i.e., the number of trials
394 that are event-free at the start of the bin), the number of observed events, and the
395 estimates of $h(t)$, $S(t)$, $P(t)$, possibly $ca(t)$, and their estimated standard errors (se). At
396 time point zero, no events can occur and therefore $h(t)$ and $ca(t)$ are undefined.

397 Figure 4 displays the discrete-time hazard, survivor, conditional accuracy, and
398 probability mass functions for each prime condition for participant 6. By using
399 discrete-time hazard functions of event occurrence – in combination with conditional
400 accuracy functions for two-choice tasks – one can provide an unbiased, time-varying, and
401 probabilistic description of the latency and accuracy of responses based on all trials of any
402 data set.

403 For example, for participant 6, the estimated hazard values in bin (240,280] are 0.03,
404 0.17, and 0.20 for the blank, congruent, and incongruent prime conditions, respectively. In
405 other words, when the waiting time has increased until *240 ms* after target onset, then the

406 conditional probability of response occurrence in the next 40 ms is more than five times
407 larger for both prime-present conditions, compared to the blank prime condition.

408 Furthermore, the estimated conditional accuracy values in bin (240,280] are 0.29, 1,
409 and 0 for the blank, congruent, and incongruent prime conditions, respectively. In other
410 words, if a response is emitted in bin (240,280], then the probability that it is correct is
411 estimated to be 0.29, 1, and 0 for the blank, congruent, and incongruent prime conditions,
412 respectively.

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. se = standard error. ca = conditional accuracy.

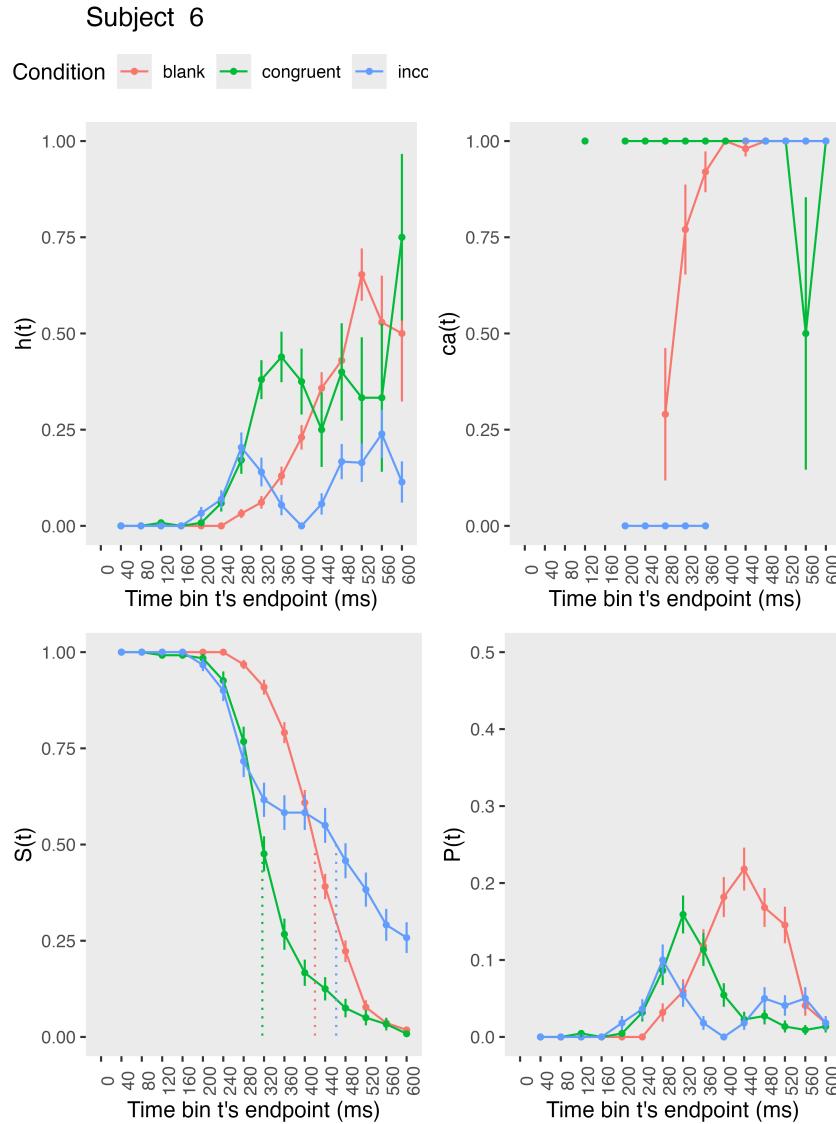


Figure 4. Estimated discrete-time hazard, survivor, probability mass, and conditional accuracy functions for participant 6, as a function of the passage of discrete waiting time.

413 However, when the waiting time has increased until 400 ms after target onset, then
 414 the conditional probability of response occurrence in the next 40 ms is estimated to be
 415 0.36, 0.25, and 0.06 for the blank, congruent, and incongruent prime conditions,
 416 respectively. And when a response does occur in bin (400,440], then the probability that it
 417 is correct is estimated to be 0.98, 1, and 1 for the blank, congruent, and incongruent prime

418 conditions, respectively.

419 These distributional results suggest that the participant 6 is initially responding to
420 the prime even though (s)he was instructed to only respond to the target, that response
421 competition emerges in the incongruent prime condition around 300 ms, and that only
422 slower responses are fully controlled by the target stimulus. Qualitatively similar results
423 were obtained for the other five participants. When participants show qualitatively the
424 same distributional patterns, one might consider to aggregate their data and make one plot
425 (see Tutorial_1a.Rmd).

426 In general, these results go against the (often implicit) assumption in research on
427 priming that all observed responses are primed responses to the target stimulus. Instead,
428 the distributional data show that early responses are triggered exclusively by the prime
429 stimulus, while only later responses reflect primed responses to the target stimulus.

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

436 4.2 Tutorial 1b: Generalising to a more complex design

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

443 To this end, Tutorial 1b illustrates how to calculate and plot the descriptive statistics
444 for the full data set of Experiment 1 of Panis and Schmidt (2016), which includes two
445 independent variables: mask type and prime type. As we use the same functional
446 programming approach as in Tutorial 1a, we simply present the sample-based functions for
447 participant 6 as part of Tutorial 1b for those that are interested.

448 **4.3 Tutorial 2a: Fitting Bayesian hazard models to time-to-event data**

449 In this third tutorial, we illustrate how to fit Bayesian multi-level regression models
450 to the RT data of the masked response priming data set used in Tutorial 1a. Fitting
451 (Bayesian or non-Bayesian) regression models to time-to-event data is important when you
452 want to study how the shape of the hazard function depends on various predictors (Singer
453 & Willett, 2003).

454 **4.3.1 Hazard model considerations.** There are several analytic decisions one
455 has to make when fitting a hazard model. First, one has to select an analysis time window,
456 i.e., a contiguous set of bins for which there is enough data for each participant. Second,
457 given that the dependent variable (event occurrence) is binary, one has to select a link
458 function (see part C in the supplementary material). The cloglog link is preferred over the
459 logit link when events can occur in principle at any time point within a bin, which is the
460 case for RT data (Singer & Willett, 2003). Third, one has to choose a specification of the
461 effect of discrete TIME (i.e., the time bin index t) in a selected baseline condition. One can
462 choose a general specification (one intercept per bin) or a functional specification, such as a
463 polynomial one (compare model 1 with models 2, 3, and 4 below; see also part D of the
464 supplementary material).

465 In the case of a large- N design without repeated measurements, the parameters of a
466 discrete-time hazard model can be estimated using standard logistic regression software
467 after expanding the typical person-trial data set into a person-trial-bin data set (Allison,
468 2010). When there is clustering in the data, as in the case of a small- N design with

469 repeated measurements, the parameters of a discrete-time hazard model can be estimated
 470 using population-averaged methods (e.g., Generalized Estimating Equations), and Bayesian
 471 or frequentist generalized linear mixed models (Allison, 2010).

472 In general, there are three assumptions one can make or relax when adding
 473 experimental predictor variables and other covariates: The linearity assumption for
 474 continuous predictors (the effect of a 1 unit change is the same anywhere on the scale), the
 475 additivity assumption (predictors do not interact), and the proportionality assumption
 476 (predictors do not interact with TIME).

477 In this tutorial we will fit four Bayesian multilevel models (i.e., generalized linear
 478 mixed models) that differ in complexity to the person-trial-bin oriented data set that we
 479 created in Tutorial 1a. We decided to select the analysis time window (200,600] and the
 480 cloglog link. The data is prepared as follows.

```
# load person-trial-bin oriented data set
ptb_data <- read_csv("../Tutorial_1_descriptive_stats/data/inputfile_hazard_modeling.csv")

# select analysis time window: (200,600] with 10 bins (time bin ranks 6 to 15)
ptb_data <- ptb_data %>% filter(period > 5)

# create factor condition, with "blank" as the reference level
ptb_data <- ptb_data %>% mutate(condition = factor(condition, labels = c("blank", "congruent", "incongruent")))

# center TIME (variable period) on bin 9, and variable trial on number 1000 and rescale; Add dummy variables for each bin.
ptb_data <- ptb_data %>%
  mutate(period_9 = period - 9,
         trial_c = (trial - 1000)/1000,
         d6 = if_else(period == 6, 1, 0),
         d7 = if_else(period == 7, 1, 0),
         d8 = if_else(period == 8, 1, 0),
         d9 = if_else(period == 9, 1, 0),
         d10 = if_else(period == 10, 1, 0),
         d11 = if_else(period == 11, 1, 0),
         d12 = if_else(period == 12, 1, 0),
         d13 = if_else(period == 13, 1, 0),
         d14 = if_else(period == 14, 1, 0),
         d15 = if_else(period == 15, 1, 0))
```

481 **4.3.2 Prior distributions.** To get the posterior distribution of each model

482 parameter given the data, we need to specify a prior distribution for each parameter. The
 483 middle column of Figure 12 in part E of the supplementary material shows seven examples
 484 of prior distributions on the logit and/or cloglog scales.

485 While a normal distribution with relatively large variance is often used as a weakly

486 informative prior for continuous dependent variables, rows A and B in Figure 12 show that
 487 specifying such distributions on the logit and cloglog scales leads to rather informative
 488 distributions on the original probability scale, as most mass is pushed to probabilities of 0
 489 and 1. The other rows in Figure 12 show prior distributions on the logit and cloglog scale
 490 that we use instead.

491 **4.3.3 Model 1: A general specification of TIME, and main effects of**

492 **congruency and trial number.** When you do not want to make assumptions about the
 493 shape of the hazard function in the selected baseline condition, or its shape is not smooth
 494 but irregular, then you can use a general specification of TIME, i.e., fit one intercept per
 495 time bin. In this first model, we use a general specification of TIME for the selected
 496 baseline condition (blank prime), and assume that the effects of prime-target congruency
 497 and trial number are proportional and additive, and that the effect of trial number is
 498 linear. Before we fit model 1, we remove unnecessary columns from the data, and specify
 499 our priors. In the code of Tutorial 2a, model M1 is specified as follows.

```
model_M1 <-
  brm(data = M1_data,
       family = binomial(link="cloglog"),
       event | trials(1) ~ 0 + d6 + d7 + d8 + Intercept + d10 + d11 + d12 + d13 + d14 + d15 +
              condition + trial_c +
              (d6 + d7 + d8 + 1 + d10 + d11 + d12 + d13 + d14 + d15 +
               condition + trial_c | pid),
       prior = priors_M1,
       chains = 4, cores = 4, iter = 3000, warmup = 1000,
       control = list(adapt_delta = 0.999, step_size = 0.04, max_treedepth = 12),
       seed = 12, init = "O",
```

```
file = "Tutorial_2_Bayesian/models/model_M1")
```

500 After selecting the binomial family and the cloglog link, the model formula is
 501 specified. The fixed effects include 9 dummy variables, the explicit Intercept variable
 502 (which represents bin 9 in this example), and the main effects of prime-target congruency
 503 (variable condition) and centered trial number (variable trial_c). Each of these effects is
 504 allowed to vary across individuals (variable pid). Estimating model M1 took about 70
 505 minutes on a MacBook Pro (Sonoma 14.6.1 OS, 18GB Memory, M3 Pro Chip).

506 **4.3.4 Model 2: A polynomial specification of TIME, and main effects of**
 507 **congruency and trial number.** When the shape of the hazard function is rather
 508 smooth, as it is for behavioral RT data, one can fit a more parsimonious model by using a
 509 polynomial specification of TIME. For our second example model, we thus use a
 510 third-order polynomial specification of TIME for the selected baseline condition (blank
 511 prime), and again assume that the effects of prime-target congruency and centered trial
 512 number are proportional and additive, and that the effect of trial number is linear. The
 513 model formula for model M2 looks as follows.

```
event | trials(1) ~ 0 + Intercept + period_9 + I(period_9^2) + I(period_9^3) +  

       condition + trial_c +  

       (1 + period_9 + I(period_9^2) + I(period_9^3) +  

       condition + trial_c | pid),
```

514 Because TIME is centered on bin 9, and trial number on trial 1000, the Intercept
 515 represents the cloglog-hazard in bin 9 for the blank prime condition in trial 1000.
 516 Estimating model M2 took about 2.5 hours.

517 **4.3.5 Model 3: A polynomial specification of TIME, and relaxing the**
 518 **proportionality assumption.** So far, we assumed that the effect of our predictors
 519 prime-target congruency and centered trial number are the same in each time bin. However,
 520 the descriptive plots (e.g., Figure 4) suggest that the effect of prime-target congruency

521 varies across time bins. Previous research has shown that psychological effects typically
 522 change over time (Panis, 2020; Panis, Moran, et al., 2020; Panis & Schmidt, 2022; Panis et
 523 al., 2017; Panis & Wagemans, 2009). For the third model, we thus use a third-order
 524 polynomial specification of TIME for the baseline condition (blank prime), and relax the
 525 proportionality assumption for the predictor variables prime-target congruency (variable
 526 condition) and centered trial number (variable trial_c).

```
event | trials(1) ~ 0 + Intercept +
      condition*period_9 +
      condition*I(period_9^2) +
      condition*I(period_9^3) +
      trial_c*period_9 +
      trial_c*I(period_9^2) +
      trial_c*I(period_9^3) +
      (1 + condition*period_9 +
      condition*I(period_9^2) +
      condition*I(period_9^3) +
      trial_c*period_9 +
      trial_c*I(period_9^2) +
      trial_c*I(period_9^3) | pid),
```

527 Note that duplicate terms across the interaction terms in the model formula (e.g.,
 528 condition) are ignored. Estimating model M3 took about 4.5 hours.

529 **4.3.6 Model 4: A polynomial specification of TIME, and relaxing all three
 530 assumptions.** Based on previous work (e.g., Panis, 2020) we expect nonlinear effects of
 531 trial number on the hazard of response occurrence. We thus relax all three assumptions in
 532 model 4. We add a squared term for the continuous predictor centered trial number –
 533 $I(trial_c^2)$ – and include interaction terms. For example, how the effect of congruent
 534 primes changes across time bins within a trial might change across the trials within an
 535 experiment.

```
event | trials(1) ~ 0 + Intercept +
      condition*period_9*trial_c +
      condition*period_9*I(trial_c^2) +
```

```

condition*I(period_9^2)*trial_c +
condition*I(period_9^2)*I(trial_c^2) +
condition*I(period_9^3) +
trial_c*I(period_9^3) +
(1 + condition*period_9*trial_c +
condition*period_9*I(trial_c^2) +
condition*I(period_9^2)*trial_c +
condition*I(period_9^2)*I(trial_c^2)
condition*I(period_9^3) +
trial_c*I(period_9^3) | pid)

```

536 Again, duplicate terms across the interaction terms in the model formula are ignored.

537 Estimating model M4 took about 8 hours.

538 **4.3.7 Compare the models.** We can compare the four models using the Widely
 539 Applicable Information Criterion (WAIC) and Leave-One-Out (LOO) cross-validation, and
 540 look at model weights for both criteria (Kurz, 2023a; McElreath, 2018).

```
model_weights(model_M1, model_M2, model_M3, model_M4, weights = "loo") %>% round(digits = 3)
```

```
541 ## model_M1 model_M2 model_M3 model_M4
542 ##      0      0      0      1
```

```
model_weights(model_M1, model_M2, model_M3, model_M4, weights = "waic") %>% round(digits = 3)
```

```
543 ## model_M1 model_M2 model_M3 model_M4
544 ##      0      0      0      1
```

545 Clearly, both the loo and waic weighting schemes assign a weight of 1 to model M4,
 546 and a weight of 0 to the other three simpler models.

547 **4.3.8 Evaluate parameter estimates.** To make inferences from the parameter
 548 estimates in model M4, we summarize the draws from the posterior distributions of the
 549 effects of congruent and incongruent primes relative to the blank prime condition, in each
 550 time bin for trial numbers 500, 1000, and 1500, in terms of point and interval estimates.

551 Figure 6 shows one point (mean) and three highest posterior density interval

552 (50/80/95%) estimates for the effects of congruent and incongruent primes relative to

553 neutral primes, for each time bin in trial numbers 500, 1000, and 1500.

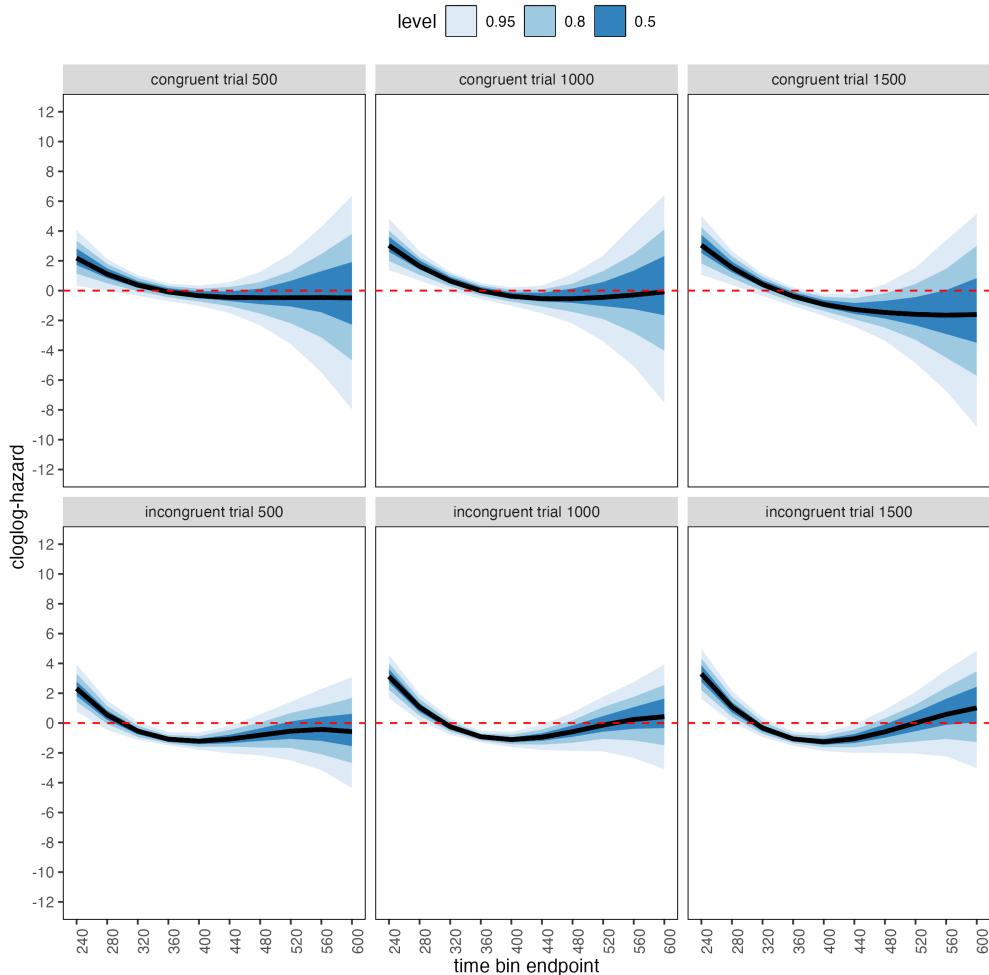


Figure 5. Means and 50/80/95% highest posterior density intervals of the draws from the posterior distributions representing the effect of congruent and incongruent primes relative to neutral primes in each bin for trial numbers 500, 1000, and 1500.

554 Table 4 shows the summaries of the draws from the posterior distributions of the

555 effects of congruent and incongruent primes relative to the blank prime condition in trials

556 500, 1000, and 1500, in terms of a point estimate (the mean) and the upper and lower

557 bounds of the 95% highest posterior density interval. Also, by exponentiating the mean we

558 obtain an effect size in terms of a hazard ratio. For simplicity and ease of presentation, we
559 only tabulate data for a subset of the design in the main text (trial 500 for congruent and
560 incongruent conditions). For the full table, see Supplementary materials or Tutorial X.

561 Based on Figure 6 and Supplementary Table XX, we see that at the beginning of the
562 experiment (trial 500), congruent and incongruent primes have a positive effect in time bin
563 (200,240] on cloglog-hazard, relative to the cloglog-hazard estimate in the baseline
564 condition (no prime; red striped lines in Figure 6). For example, the hazard ratio shows
565 that the hazard of response occurrence for congruent primes is estimated to be 8.82 times
566 higher than that for no-prime trials in bin (200,240] of trial 500. Incongruent primes also
567 have a negative effect on cloglog-hazard in bins (320,360], (360,400], and (400,440]. For
568 example, in bin (320,360], the hazard ratio shows that the hazard of response occurrence
569 for incongruent prime is estimated to be .34 times smaller than that for no-prime trials.
570 While the early positive effects reflect responses to the prime stimulus, the later negative
571 effect for incongruent primes likely reflects response competition between the
572 prime-triggered response (e.g., left) and the target-triggered response (e.g., right)

573 In the middle of the experiment (trial 1000), both congruent and incongruent primes
574 have positive effects in bins (200,240] and (240,280], while incongruent primes again have
575 negative effects in bins (320,360], (360,400], and (400,440]. Probably due to practicing
576 stimulus-response associations, the primes generate a higher hazard of response occurrence
577 for 80 ms early in a trial (compared to 40 ms at the beginning of the experiment)
578 compared to the blank prime condition.

579 Towards the end of the experiment (trial 1500), both congruent and incongruent
580 primes have positive and negative effects. Positive effects are present in bins (200,240] and
581 (240,280]. Incongruent primes again have negative effects in bins (320,360], (360,400], and
582 (400,440], and congruent primes now also have negative effects in bins (360,400] and
583 (400,440].

These results show that the effect of prime-target congruency changes not only on the across-bin/within-trial time scale (variable period_9), but also on the across-trial/within-experiment time scale (variable trial_c). The fact that congruent primes generate negative effects for 80 ms (compared to no-prime trials) towards the end of the experiment, while incongruent primes generate negative effects for 120 ms throughout the experiment, suggests the involvement of separate cognitive processes.

Panis and Schmidt (2016) distinguished between automatic response competition (bottom-up lateral inhibition between response channels), active and global inhibition (top-down nonselective response inhibition), and active and selective inhibition (top-down selective response inhibition). While automatic response competition can be expected to be present in the incongruent trials throughout the experiment, active and global response inhibition effects might be present in both congruent and incongruent (unmasked) prime trials. In other words, people learn that the prime-triggered response is premature and that they have to temporarily slow down (increase the global response threshold) in order to allow gating of the correct response to the target stimulus. Thus, it seems that this global inhibitory effect becomes visible in the congruent (compared to no-prime) trials towards the end of the experiment, while it might be masked by the automatic inhibitory effect of response competition in the incongruent trials. Interestingly, while Panis and Schmidt (2016) did not test interactions between prime-target congruency and trial number, they concluded that active (i.e., top-down) response inhibition starts around 360 ms after the onset of the second stimulus (the target stimulus in no-mask trials), which nicely coincides with the onset of the negative effect of congruent primes observed here in trial 1500.

To conclude this Tutorial 2a, Figure 7 shows the model-based hazard functions for each prime type for participant 6, in trials 500, 1000, and 1500.

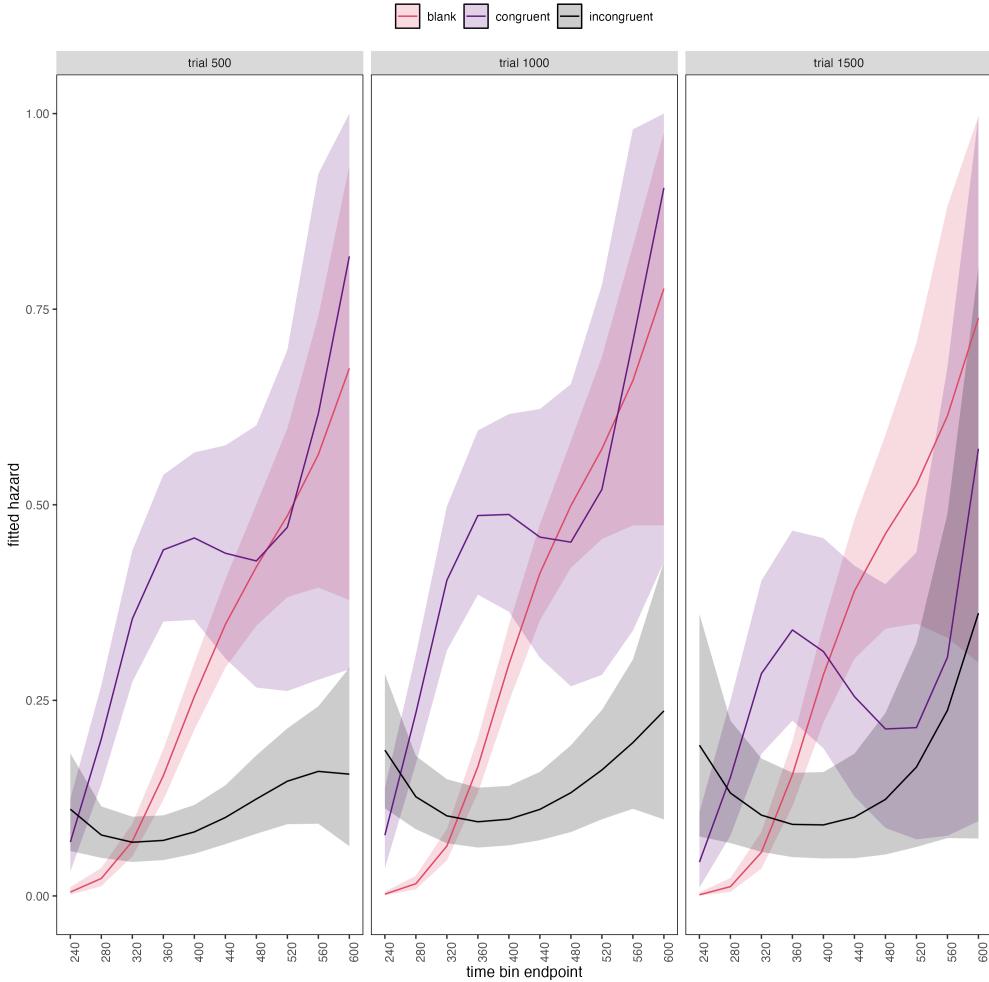


Figure 6. Model-based hazard functions for each prime type for participant 6 in trials 500, 1000, and 1500.

608 4.4 Tutorial 2b: Fitting Bayesian conditional accuracy models

609 In this fourth tutorial, we illustrate how to fit a Bayesian multi-level regression model
 610 to the timed accuracy data from the masked response priming data set used in Tutorial 1a.
 611 The general process is similar to Tutorial 2a, except that (a) we use the person-trial data
 612 set, (b) we use the logit link function, and (c) we change the priors. For illustration
 613 purposes, we only fitted the effects of model M4 (see Tutorial 2a) in the conditional
 614 accuracy model called M4_ca.

615 To make inferences from the parameter estimates in model M4_ca, we summarize the
 616 draws from the posterior distributions of the effects of congruent and incongruent primes
 617 on logit-ca relative to the blank prime condition, in each time bin for trial numbers 500,
 618 1000, and 1500, in terms of point and interval estimates.

619 Figure 8 shows one point (mean) and three highest posterior density interval
 620 (50/80/95%) estimates for the effects of congruent and incongruent primes relative to
 621 neutral primes on logit-ca, for each time bin in trial numbers 500, 1000, and 1500.

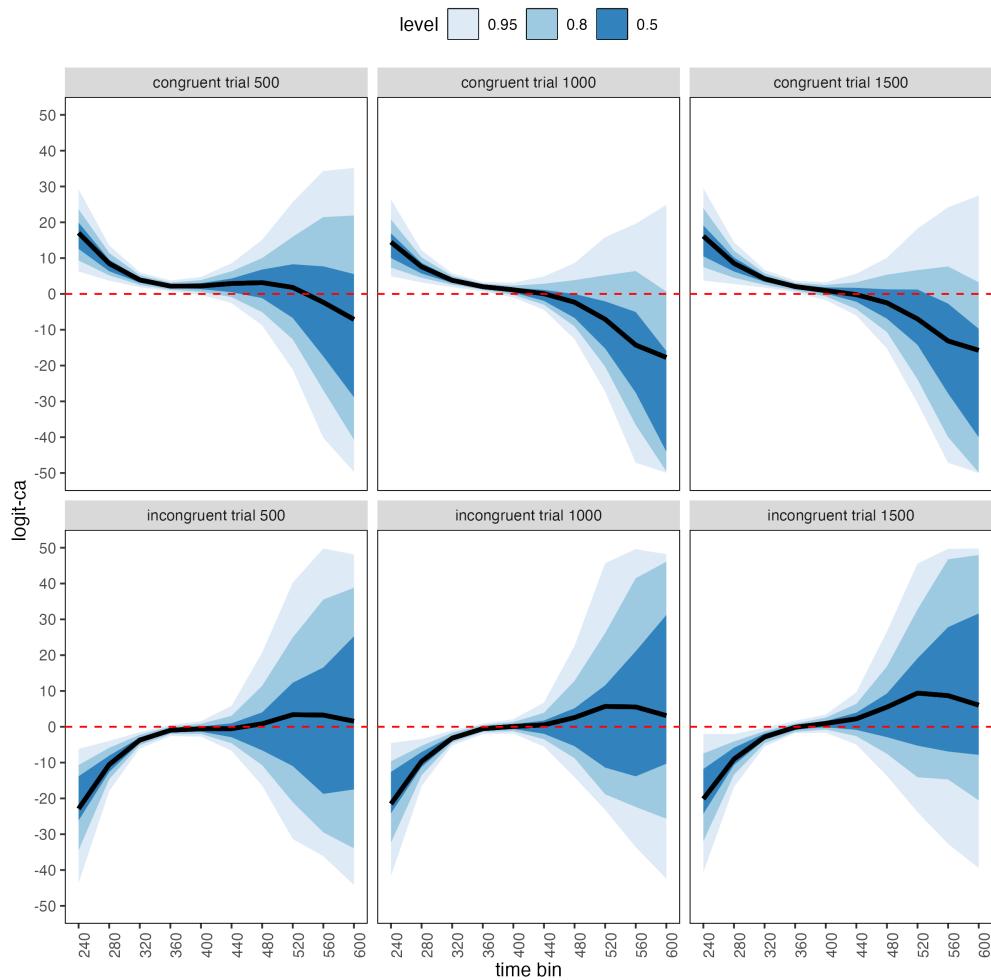


Figure 7. Means and 50/80/95% highest posterior density intervals of the draws from the posterior distributions representing the effect of congruent and incongruent primes relative to neutral primes in each bin for trial numbers 500, 1000, and 1500.

622 Supplementary Table XX shows the summaries of the draws from the posterior
623 distributions of the effects of congruent and incongruent primes relative to the blank prime
624 condition in trials 500, 1000, and 1500, in terms of a point estimate (the mean) and the
625 upper and lower bounds of the 95% highest posterior density interval. Also, by
626 exponentiating the mean we obtain an effect size in terms of an odds ratio.

627 Based on Figure 8 and Supplementary Table XX, we see that throughout the
628 experiment (trials 500, 1000, and 1500), congruent primes have a positive effect on
629 logit-ca(t) in time bins (200,240], (240,280], (280,320], and (320,360], relative to the
630 logit-ca(t) estimates in the baseline condition (blank prime; red dashed lines in Figure 8).
631 For example, the odds ratio for congruent primes in bin (320,360] in trial 500 shows that
632 the odds of a correct response are estimated to be 8.89 times higher than the odds of a
633 correct response when there is no prime. Incongruent primes have a negative effect on
634 logit-ca(t) in time bins (200,240], (240,280], and (280,320] throughout the experiment,
635 relative to the logit-ca(t) estimates in the baseline condition (no prime; red striped lines).

636 To conclude this Tutorial 2b, Figure 9 shows the model-based ca(t) functions for each
637 prime type for participant 6, in trials 500, 1000, and 1500.

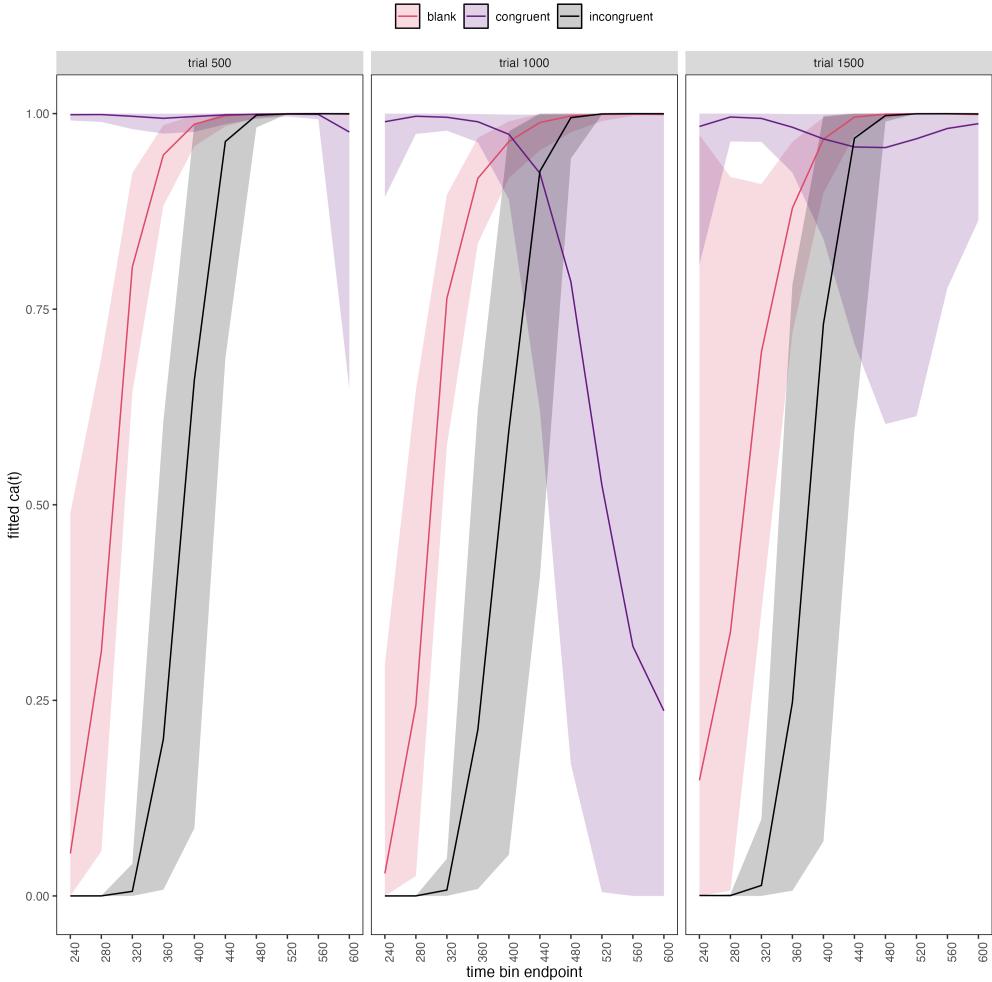


Figure 8. Model-based $ca(t)$ functions for each prime type for participant 6 in trials 500, 1000, and 1500.

638 4.5 Tutorial 3a: Fitting Frequentist hazard models

639 In this fifth tutorial we illustrate how to fit a multilevel regression model to RT data
 640 in the frequentist framework, for the data set used in Tutorial 1a. The general process is
 641 similar to that in Tutorial 2a, except that there are no priors to set. Because we expected
 642 that the random effects structure of model M4 would be too complex for a frequentist
 643 approach, we only fitted the effects from model M3 (see Tutorial 2a) using the function
 644 `glmer()` from the R package `lme4`. Alternatively, one could also use the function

645 glmmPQL() from the R package MASS (Ripley et al., 2024). The resulting hazard model
 646 is called M3_f.

647 In Figure 10 we compare the parameter estimates of model M3 from brm() with those
 648 of model M3_f from glmer().

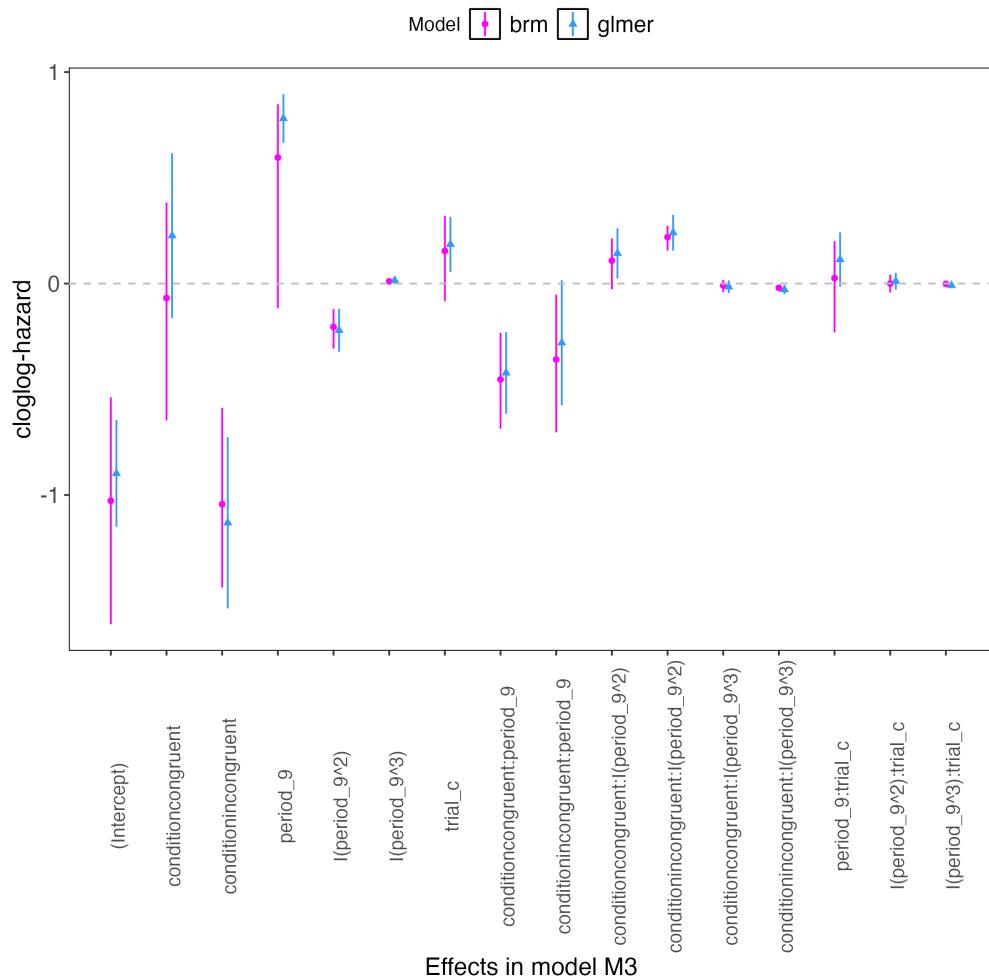


Figure 9. Parameter estimates for model M3 from brm() – means and 95% quantile intervals – and model M3_f from glmer() – maximum likelihood estimates and 95% confidence intervals.

649 Figure 10 confirms that the parameter estimates from both Bayesian and frequentist
 650 models are pretty similar, which makes sense given the close similarity in model structure.
 651 However, the random effects structure of model M3_f was already too complex for the

652 frequentist model as it did not converge and resulted in a singular fit. This is of course one
653 of the reasons why Bayesian modeling has become so popular in recent years. But the price
654 you pay for being able to fit more complex random effects models in a Bayesian framework
655 is computation time. In other words, as we have noted throughout, some of the Bayesian
656 models in Tutorials 2a and 2b took several hours to build.

657 **4.6 Tutorial 3b: Fitting Frequentist conditional accuracy models**

658 In this sixth tutorial we illustrate how to fit a multilevel regression model to the
659 timed accuracy data in the frequentist framework, for the data set used in Tutorial 1a. For
660 illustration purposes, we only fitted the effects from model M3 (see Tutorial 2a) using the
661 function `glmer()` from the R package `lme4`. Alternatively, one could also use the function
662 `glmmPQL()` from the R package `MASS` (Ripley et al., 2024). Again, the resulting
663 conditional accuracy model `M3_ca_f` did not converge and resulted in a singular fit.

664 **4.4 Tutorial 4: Planning**

665 This needs adding... RR to do this.

666 **5. Discussion**

667 This main motivation for writing this paper is the observation that EHA and SAT
668 analysis remain under-used in psychological research. As a consequence, the field of
669 psychological research is not taking full advantage of the many benefits EHA/SAT provides
670 compared to more conventional analyses. By providing a freely available set of tutorials,
671 which provide step-by-step guidelines and ready-to-use R code, we hope that researchers
672 will feel more comfortable using EHA/SAT in the future. Indeed, we hope that our
673 tutorials may help to overcome a barrier to entry with EHA/SAT, which is that such
674 approaches require more analytical complexity compared to mean-average comparisons.

675 While we have focused here on within-subject, factorial, small- N designs, it is important to
676 realize that EHA/SAT can be applied to other designs as well (large- N designs with only
677 one measurement per subject, between-subject designs, etc.). As such, the general workflow
678 and associated code can be modified and applied more broadly to other contexts and
679 research questions. In the following, we discuss issues relating to model complexity and
680 interpretability, individual differences, as well as limitations of the approach and future
681 extensions.

682 **5.1 What are the main use-cases of EHA for understanding cognition and brain
683 function?**

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

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

700 **5.2 Model complexity versus interpretability**

701 EHA can quickly become very complex when adding more than 1 time scale, due to
702 the many possible higher-order interactions. For example, model M4 contains two time
703 scales as covariates: the passage of time on the within-trial time scale, and the passage of
704 time on the across-trial (or within-experiment) time scale. However, when trials are
705 presented in blocks, and blocks of trials within sessions, and when the experiment
706 comprises three sessions, then four time scales can be defined (within-trial, within-block,
707 within-session, and within-experiment). From a theoretical perspective, adding more than
708 1 time scale – and their interactions – can be important to capture plasticity and other
709 learning effects that may play out on such longer time scales, and that are probably present
710 in each experiment in general. From a practical perspective, therefore, some choices need
711 to be made to balance the amount of data that is being collected per participant, condition
712 and across the varying timescales. As one example, if there are several timescales of
713 relevance, then it might be prudent for interpretational purposes to limit the number of
714 experimental predictor variables (conditions). This is of course where planning and data
715 simulation efforts would be important to provide a guide to experimental design choices.

716 **5.3 Individual differences**

717 One important issue is that of possible individual differences in the overall location of
718 the distribution, and the time course of psychological effects. For example, when you wait
719 for a response of the participant on each trial, you allow the participant to have control
720 over the trial duration, and some participants might respond only when they are confident
721 that their emitted response will be correct. These issues can be avoided by introducing a
722 (relatively short) response deadline in each trial, e.g., 600 ms for simple detection tasks,
723 1000 ms for more difficult discrimination tasks, or 2 s for tasks requiring extended high-level
724 processing. Because EHA can deal in a straightforward fashion with right-censored

725 observations (i.e., trials without an observed response), introducing a response deadline is
726 recommended when designing RT experiments. Furthermore, introducing a response
727 deadline and asking participants to respond before the deadline as much as possible, will
728 also lead to individual distributions that overlap in time, which is important when selecting
729 a common analysis time window when fitting hazard and conditional accuracy models.

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

739 Another approach to deal with individual differences is Bayesian prevalence (Ince,
740 Paton, Kay, & Schyns, 2021), which is a from of Small-N approach (Smith & Little, 2018).
741 This method looks at effects within each individual in the study and asks how likely it
742 would be to see the same result if the experiment was repeated with a new person chosen
743 from the wider population at random. This approach allows one to quantify how typical or
744 uncommon an observed effect is in the population, and the uncertainty around this
745 estimate.

746 5.4 Limitations

747 Compared to the orthodox method – comparing mean-averages between conditions –
748 the most important limitation of multi-level hazard and conditional accuracy modeling is
749 that it might take a long time to estimate the parameters using Bayesian methods or the

750 model might have to be simplified significantly to use frequentist methods.

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

764 We did not discuss continuous-time EHA, nor continuous-time SAT analysis. As
765 indicated by Allison (2010), learning discrete-time EHA methods first will help in learning
766 continuous-time methods. Given that RT is typically treated as a continuous variable, it is
767 possible that continuous-time methods will ultimately prevail. However, they require much
768 more data to estimate the continuous-time hazard (rate) function well. Thus, by trading a
769 bit of temporal resolution for a lower number of trials, discrete-time methods seem ideal for
770 dealing with typical psychological time-to-event data sets for which there are less than
771 ~200 trials per condition per experiment.

772 5.5 Extensions

773 The hazard models in this tutorial assume that there is one event of interest. For RT
774 data, this event constitutes a single transition between an “idle” state and a “responded”

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

788

6. Conclusions

789 Estimating the temporal distributions of RT and accuracy provide a rich source of
790 information on the time course of cognitive processing, which have been largely
791 undervalued in the history of experimental psychology and cognitive neuroscience.
792 Statistically controlling for the passage of time during data analysis is equally important as
793 experimental control during the design of an experiment, to better understand human
794 behavior in experimental paradigms. We hope that by providing a set of hands-on,
795 step-by-step tutorials, which come with custom-built and freely available code, researchers
796 will feel more comfortable embracing EHA and investigating the temporal profile of
797 cognitive states. On a broader level, we think that wider adoption of such approaches will
798 have a meaningful impact on the inferences drawn from data, as well as the development of
799 theories regarding the structure of cognition.

800

References

- 801 Allison, P. D. (1982). Discrete-Time Methods for the Analysis of Event Histories.
- 802 *Sociological Methodology*, 13, 61. <https://doi.org/10.2307/270718>
- 803 Allison, P. D. (2010). *Survival analysis using SAS: A practical guide* (2. ed). Cary, NC:
- 804 SAS Press.
- 805 Aust, F. (2019). *Citr: 'RStudio' add-in to insert markdown citations*. Retrieved from
- 806 <https://github.com/crsh/citr>
- 807 Aust, F., & Barth, M. (2023). *papaja: Prepare reproducible APA journal articles with R*
- 808 *Markdown*. Retrieved from <https://github.com/crsh/papaja>
- 809 Aust, F., & Barth, M. (2024). *papaja: Prepare reproducible APA journal articles with R*
- 810 *Markdown*. <https://doi.org/10.32614/CRAN.package.papaja>
- 811 Baker, D. H., Vilidaite, G., Lygo, F. A., Smith, A. K., Flack, T. R., Gouws, A. D., &
- 812 Andrews, T. J. (2021). Power contours: Optimising sample size and precision in
- 813 experimental psychology and human neuroscience. *Psychological Methods*, 26(3),
- 814 295–314. <https://doi.org/10.1037/met0000337>
- 815 Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for
- 816 confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*,
- 817 68(3), 10.1016/j.jml.2012.11.001. <https://doi.org/10.1016/j.jml.2012.11.001>
- 818 Barth, M. (2023). *tinylabes: Lightweight variable labels*. Retrieved from
- 819 <https://cran.r-project.org/package=tinylabes>
- 820 Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects
- 821 models using lme4. *Journal of Statistical Software*, 67(1), 1–48.
- 822 <https://doi.org/10.18637/jss.v067.i01>
- 823 Bates, D., Maechler, M., & Jagan, M. (2024). *Matrix: Sparse and dense matrix classes and*
- 824 *methods*. Retrieved from <https://CRAN.R-project.org/package=Matrix>
- 825 Bengtsson, H. (2021). A unifying framework for parallel and distributed processing in r
- 826 using futures. *The R Journal*, 13(2), 208–227. <https://doi.org/10.32614/RJ-2021-048>

- 827 Blossfeld, H.-P., & Rohwer, G. (2002). *Techniques of event history modeling: New
828 approaches to causal analysis, 2nd ed* (pp. x, 310). Mahwah, NJ, US: Lawrence
829 Erlbaum Associates Publishers.
- 830 Box-Steffensmeier, J. M. (2004). Event history modeling: A guide for social scientists.
831 Cambridge: University Press.
- 832 Bürkner, P.-C. (2017). brms: An R package for Bayesian multilevel models using Stan.
833 *Journal of Statistical Software*, 80(1), 1–28. <https://doi.org/10.18637/jss.v080.i01>
- 834 Bürkner, P.-C. (2018). Advanced Bayesian multilevel modeling with the R package brms.
835 *The R Journal*, 10(1), 395–411. <https://doi.org/10.32614/RJ-2018-017>
- 836 Bürkner, P.-C. (2021). Bayesian item response modeling in R with brms and Stan. *Journal
837 of Statistical Software*, 100(5), 1–54. <https://doi.org/10.18637/jss.v100.i05>
- 838 Eddelbuettel, D., & Balamuta, J. J. (2018). Extending R with C++: A Brief Introduction
839 to Rcpp. *The American Statistician*, 72(1), 28–36.
840 <https://doi.org/10.1080/00031305.2017.1375990>
- 841 Eddelbuettel, D., & François, R. (2011). Rcpp: Seamless R and C++ integration. *Journal
842 of Statistical Software*, 40(8), 1–18. <https://doi.org/10.18637/jss.v040.i08>
- 843 Gabry, J., Češnovar, R., Johnson, A., & Broder, S. (2024). *Cmdstanr: R interface to
844 'CmdStan'*. Retrieved from <https://github.com/stan-dev/cmdstanr>
- 845 Gabry, J., Simpson, D., Vehtari, A., Betancourt, M., & Gelman, A. (2019). Visualization
846 in bayesian workflow. *J. R. Stat. Soc. A*, 182, 389–402.
847 <https://doi.org/10.1111/rssa.12378>
- 848 Gelman, A., Hill, J., & Vehtari, A. (2020). Regression and Other Stories.
849 <https://www.cambridge.org/highereducation/books/regression-and-other-stories/DD20DD6C9057118581076E54E40C372C>; Cambridge University Press.
850 <https://doi.org/10.1017/9781139161879>
- 852 Girard, J. (2024). *Standist: What the package does (one line, title case)*. Retrieved from
853 <https://github.com/jmgirard/standist>

- 854 Grolemund, G., & Wickham, H. (2011). Dates and times made easy with lubridate.
- 855 *Journal of Statistical Software*, 40(3), 1–25. Retrieved from
856 <https://www.jstatsoft.org/v40/i03/>
- 857 Holden, J. G., Van Orden, G. C., & Turvey, M. T. (2009). Dispersion of response times
858 reveals cognitive dynamics. *Psychological Review*, 116(2), 318–342.
859 <https://doi.org/10.1037/a0014849>
- 860 Hosmer, D. W., Lemeshow, S., & May, S. (2011). *Applied Survival Analysis: Regression*
861 *Modeling of Time to Event Data* (2nd ed). Hoboken: John Wiley & Sons.
- 862 Ince, R. A., Paton, A. T., Kay, J. W., & Schyns, P. G. (2021). Bayesian inference of
863 population prevalence. *eLife*, 10, e62461. <https://doi.org/10.7554/eLife.62461>
- 864 Kantowitz, B. H., & Pachella, R. G. (2021). The Interpretation of Reaction Time in
865 Information-Processing Research 1. *Human Information Processing*, 41–82.
866 <https://doi.org/10.4324/9781003176688-2>
- 867 Kay, M. (2023). *tidybayes: Tidy data and geoms for Bayesian models*.
868 <https://doi.org/10.5281/zenodo.1308151>
- 869 Kelso, J. A. S., Dumas, G., & Tognoli, E. (2013). Outline of a general theory of behavior
870 and brain coordination. *Neural Networks: The Official Journal of the International*
871 *Neural Network Society*, 37, 120–131. <https://doi.org/10.1016/j.neunet.2012.09.003>
- 872 Kruschke, J. K., & Liddell, T. M. (2018). The Bayesian New Statistics: Hypothesis testing,
873 estimation, meta-analysis, and power analysis from a Bayesian perspective.
874 *Psychonomic Bulletin & Review*, 25(1), 178–206.
875 <https://doi.org/10.3758/s13423-016-1221-4>
- 876 Kurz, A. S. (2023a). *Applied longitudinal data analysis in brms and the tidyverse* (version
877 0.0.3). Retrieved from <https://bookdown.org/content/4253/>
- 878 Kurz, A. S. (2023b). *Statistical rethinking with brms, ggplot2, and the tidyverse: Second*
879 *edition* (version 0.4.0). Retrieved from <https://bookdown.org/content/4857/>
- 880 Landes, J., Engelhardt, S. C., & Pelletier, F. (2020). An introduction to event history

- 881 analyses for ecologists. *Ecosphere*, 11(10), e03238. <https://doi.org/10.1002/ecs2.3238>
- 882 Luce, R. D. (1991). *Response times: Their role in inferring elementary mental organization*
883 (1. issued as paperback). Oxford: Univ. Press.
- 884 Makeham, William M. (1860). *On the Law of Mortality and the Construction of Annuity*
885 *Tables*. The Assurance Magazine, and Journal of the Institute of Actuaries.
- 886 McElreath, R. (2018). *Statistical Rethinking: A Bayesian Course with Examples in R and*
887 *Stan* (1st ed.). Chapman and Hall/CRC. <https://doi.org/10.1201/9781315372495>
- 888 Meyer, D. E., Osman, A. M., Irwin, D. E., & Yantis, S. (1988). Modern mental
889 chronometry. *Biological Psychology*, 26(1-3), 3–67.
890 [https://doi.org/10.1016/0301-0511\(88\)90013-0](https://doi.org/10.1016/0301-0511(88)90013-0)
- 891 Müller, K., & Wickham, H. (2023). *Tibble: Simple data frames*. Retrieved from
892 <https://CRAN.R-project.org/package=tibble>
- 893 Neuwirth, E. (2022). *RColorBrewer: ColorBrewer palettes*. Retrieved from
894 <https://CRAN.R-project.org/package=RColorBrewer>
- 895 Panis, S. (2020). How can we learn what attention is? Response gating via multiple direct
896 routes kept in check by inhibitory control processes. *Open Psychology*, 2(1), 238–279.
897 <https://doi.org/10.1515/psych-2020-0107>
- 898 Panis, S., Moran, R., Wolkersdorfer, M. P., & Schmidt, T. (2020). Studying the dynamics
899 of visual search behavior using RT hazard and micro-level speed–accuracy tradeoff
900 functions: A role for recurrent object recognition and cognitive control processes.
901 *Attention, Perception, & Psychophysics*, 82(2), 689–714.
902 <https://doi.org/10.3758/s13414-019-01897-z>
- 903 Panis, S., Schmidt, F., Wolkersdorfer, M. P., & Schmidt, T. (2020). Analyzing Response
904 Times and Other Types of Time-to-Event Data Using Event History Analysis: A Tool
905 for Mental Chronometry and Cognitive Psychophysiology. *I-Perception*, 11(6),
906 2041669520978673. <https://doi.org/10.1177/2041669520978673>
- 907 Panis, S., & Schmidt, T. (2016). What Is Shaping RT and Accuracy Distributions? Active

- 908 and Selective Response Inhibition Causes the Negative Compatibility Effect. *Journal of*
909 *Cognitive Neuroscience*, 28(11), 1651–1671. https://doi.org/10.1162/jocn_a_00998
- 910 Panis, S., & Schmidt, T. (2022). When does “inhibition of return” occur in spatial cueing
911 tasks? Temporally disentangling multiple cue-triggered effects using response history
912 and conditional accuracy analyses. *Open Psychology*, 4(1), 84–114.
913 <https://doi.org/10.1515/psych-2022-0005>
- 914 Panis, S., Torfs, K., Gillebert, C. R., Wagemans, J., & Humphreys, G. W. (2017).
915 Neuropsychological evidence for the temporal dynamics of category-specific naming.
916 *Visual Cognition*, 25(1-3), 79–99. <https://doi.org/10.1080/13506285.2017.1330790>
- 917 Panis, S., & Wagemans, J. (2009). Time-course contingencies in perceptual organization
918 and identification of fragmented object outlines. *Journal of Experimental Psychology:
919 Human Perception and Performance*, 35(3), 661–687.
920 <https://doi.org/10.1037/a0013547>
- 921 Pedersen, T. L. (2024). *Patchwork: The composer of plots*. Retrieved from
922 <https://CRAN.R-project.org/package=patchwork>
- 923 Pinheiro, J. C., & Bates, D. M. (2000). *Mixed-effects models in s and s-PLUS*. New York:
924 Springer. <https://doi.org/10.1007/b98882>
- 925 R Core Team. (2024). *R: A language and environment for statistical computing*. Vienna,
926 Austria: R Foundation for Statistical Computing. Retrieved from
927 <https://www.R-project.org/>
- 928 Ripley, B., Venables, B., Bates, D. M., ca 1998), K. H. (partial. port, ca 1998), A. G.
929 (partial. port, & polr), D. F. (support. functions for. (2024). *MASS: Support Functions
930 and Datasets for Venables and Ripley’s MASS*.
- 931 Singer, J. D., & Willett, J. B. (2003). *Applied Longitudinal Data Analysis: Modeling
932 Change and Event Occurrence*. Oxford, New York: Oxford University Press.
- 933 Smith, P. L., & Little, D. R. (2018). Small is beautiful: In defense of the small-N design.
934 *Psychonomic Bulletin & Review*, 25(6), 2083–2101.

- 935 https://doi.org/10.3758/s13423-018-1451-8
- 936 Steele, F., Goldstein, H., & Browne, W. (2004). A general multilevel multistate competing
937 risks model for event history data, with an application to a study of contraceptive use
938 dynamics. *Statistical Modelling*, 4(2), 145–159.
- 939 https://doi.org/10.1191/1471082X04st069oa
- 940 Teachman, J. D. (1983). Analyzing social processes: Life tables and proportional hazards
941 models. *Social Science Research*, 12(3), 263–301.
- 942 https://doi.org/10.1016/0049-089X(83)90015-7
- 943 Townsend, J. T. (1990). Truth and consequences of ordinal differences in statistical
944 distributions: Toward a theory of hierarchical inference. *Psychological Bulletin*, 108(3),
945 551–567. https://doi.org/10.1037/0033-2909.108.3.551
- 946 Wickelgren, W. A. (1977). Speed-accuracy tradeoff and information processing dynamics.
947 *Acta Psychologica*, 41(1), 67–85. https://doi.org/10.1016/0001-6918(77)90012-9
- 948 Wickham, H. (2016). *ggplot2: Elegant graphics for data analysis*. Springer-Verlag New
949 York. Retrieved from https://ggplot2.tidyverse.org
- 950 Wickham, H. (2023a). *Forcats: Tools for working with categorical variables (factors)*.
951 Retrieved from https://forcats.tidyverse.org/
- 952 Wickham, H. (2023b). *Stringr: Simple, consistent wrappers for common string operations*.
953 Retrieved from https://stringr.tidyverse.org
- 954 Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., ...
955 Yutani, H. (2019). Welcome to the tidyverse. *Journal of Open Source Software*, 4(43),
956 1686. https://doi.org/10.21105/joss.01686
- 957 Wickham, H., Çetinkaya-Rundel, M., & Grolemund, G. (2023). *R for data science: Import,
958 tidy, transform, visualize, and model data* (2nd edition). Beijing Boston Farnham
959 Sebastopol Tokyo: O'Reilly.
- 960 Wickham, H., François, R., Henry, L., Müller, K., & Vaughan, D. (2023). *Dplyr: A
961 grammar of data manipulation*. Retrieved from https://dplyr.tidyverse.org

- 962 Wickham, H., & Henry, L. (2023). *Purrr: Functional programming tools*. Retrieved from
963 <https://purrr.tidyverse.org/>
- 964 Wickham, H., Hester, J., & Bryan, J. (2024). *Readr: Read rectangular text data*. Retrieved
965 from <https://readr.tidyverse.org>
- 966 Wickham, H., Vaughan, D., & Girlich, M. (2024). *Tidyr: Tidy messy data*. Retrieved from
967 <https://tidyr.tidyverse.org>
- 968 Winter, B. (2019). *Statistics for Linguists: An Introduction Using R*. New York:
969 Routledge. <https://doi.org/10.4324/9781315165547>
- 970 Wolkersdorfer, M. P., Panis, S., & Schmidt, T. (2020). Temporal dynamics of sequential
971 motor activation in a dual-prime paradigm: Insights from conditional accuracy and
972 hazard functions. *Attention, Perception, & Psychophysics*, 82(5), 2581–2602.
973 <https://doi.org/10.3758/s13414-020-02010-5>

Supplementary material

975 A. Definitions of discrete-time hazard, survivor, probability mass, and
976 conditional accuracy functions

The shape of a distribution of waiting times can be described in multiple ways (Luce, 1991). After dividing time in discrete, contiguous time bins indexed by t , 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. Because waiting times can only increase, discrete-time EHA focuses on the discrete-time hazard function

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

⁹⁸³ and the discrete-time survivor function

$$984 \quad S(t) = P(RT > t) = [1-h(t)].[1-h(t-1)].[1-h(t-2)] \dots [1-h(1)] \quad (2)$$

985 and not on the probability mass function

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

987 nor the cumulative distribution function

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

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

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

999 For two-choice RT data, the discrete-time hazard function can be extended with the
 1000 discrete-time conditional accuracy function

1001 $ca(t) = P(\text{correct} \mid RT = t)$ (5)

1002 which gives you for each bin the probability that a response is correct given that it is
 1003 emitted in time bin t (Allison, 2010; Kantowitz & Pachella, 2021; Wickelgren, 1977). This
 1004 latter function is also known as the micro-level speed-accuracy tradeoff (SAT) function.

1005 The survivor function provides a context for the hazard function, as $S(t-1) = P(RT >$
 1006 $t-1) = P(RT \geq t)$ tells you on how many percent of the trials the estimate $h(t) = P(RT =$
 1007 $t \mid RT \geq t)$ is based. The probability mass function provides a context for the conditional
 1008 accuracy function, as $P(t) = P(RT = t)$ tells you on how many percent of the trials the
 1009 estimate $ca(t) = P(\text{correct} \mid RT = t)$ is based.

1010 While psychological RT data is typically measured in small, continuous units (e.g.,
 1011 milliseconds), discrete-time EHA treats the RT data as interval-censored data, because it
 1012 only uses the information that the response occurred sometime in a particular bin of time
 1013 $(x,y]: x < RT \leq y$. If we want to use the exact event times, then we treat time as a
 1014 continuous variable, and let RT be a continuous random variable denoting a particular
 1015 person's response time in a particular experimental condition. Continuous-time EHA does
 1016 not focus on the cumulative distribution function $F(t) = P(RT \leq t)$ and its derivative, the
 1017 probability density function $f(t) = F(t)'$, but on the survivor function $S(t) = P(RT > t)$
 1018 and the hazard rate function $\lambda(t) = f(t)/S(t)$. The hazard rate function gives you the
 1019 instantaneous *rate* of event occurrence at time point t, given that the event has not
 1020 occurred yet.

1021 **B. Custom functions for descriptive discrete-time hazard analysis**

1022 We defined 13 custom functions that we list here.

- 1023 • censor(df,timeout,bin_width) : divide the time segment $(0, \text{timeout}]$ in bins, identify
- 1024 any right-censored observations, and determine the discrete RT (time bin rank)
- 1025 • ptb(df) : transform the person-trial data set to the person-trial-bin data set
- 1026 • setup_lt(ptb) : set up a life table for each level of 1 independent variable
- 1027 • setup_lt_2IV(ptb) : set up a life table for each combination of levels of 2
- 1028 independent variables
- 1029 • calc_ca(df) : estimate the conditinal accuracies when there is 1 independent variable
- 1030 • calc_ca_2IV(df) : estimate the conditional accuraiies when there are 2 independent
- 1031 variables
- 1032 • join_lt_ca(df1,df2) : add the ca(t) estimates to the life tables (1 independent
- 1033 variable)
- 1034 • join_lt_ca_2IV(df1,df2) : add the ca(t) estimates to the life tables (2 independent
- 1035 variables)
- 1036 • extract_median(df) : estimate quantiles $S(t)._{50}$ (1 independent variable)
- 1037 • extract_median_2IV(df) : estimate quantiles $S(t)._{50}$ (2 independent variables)
- 1038 • plot_oha(df,subj,haz_yaxis) : create plots of the discrete-time functions (1
- 1039 independent variable)
- 1040 • plot_oha_2IV(df,subj,haz_yaxis) : create plots of the discrete-time functions (2
- 1041 independent variables)
- 1042 • plot_oha_agg(df,subj,haz_yaxis) : create 1 plot for data aggregated across
- 1043 participants (1 independent variable)

1044 When you want to analyse simple RT data from a detection experiment with one
 1045 independent variable, the functions calc_ca() and join_lt_ca() should not be used, and
 1046 the code to plot the conditional accuracy functions should be removed from the function
 1047 plot_oha(). When you want to analyse simple RT data from a detection experiment with
 1048 two independent variables, the functions calc_ca_2IV() and join_lt_ca_2IV() should not
 1049 be used, and the code to plot the conditional accuracy functions should be removed from

₁₀₅₀ the function `plot_eha_2IV()`.

₁₀₅₁ C. Link functions

₁₀₅₂ Popular link functions include the logit link and the complementary log-log link, as
₁₀₅₃ shown in Figure 11.

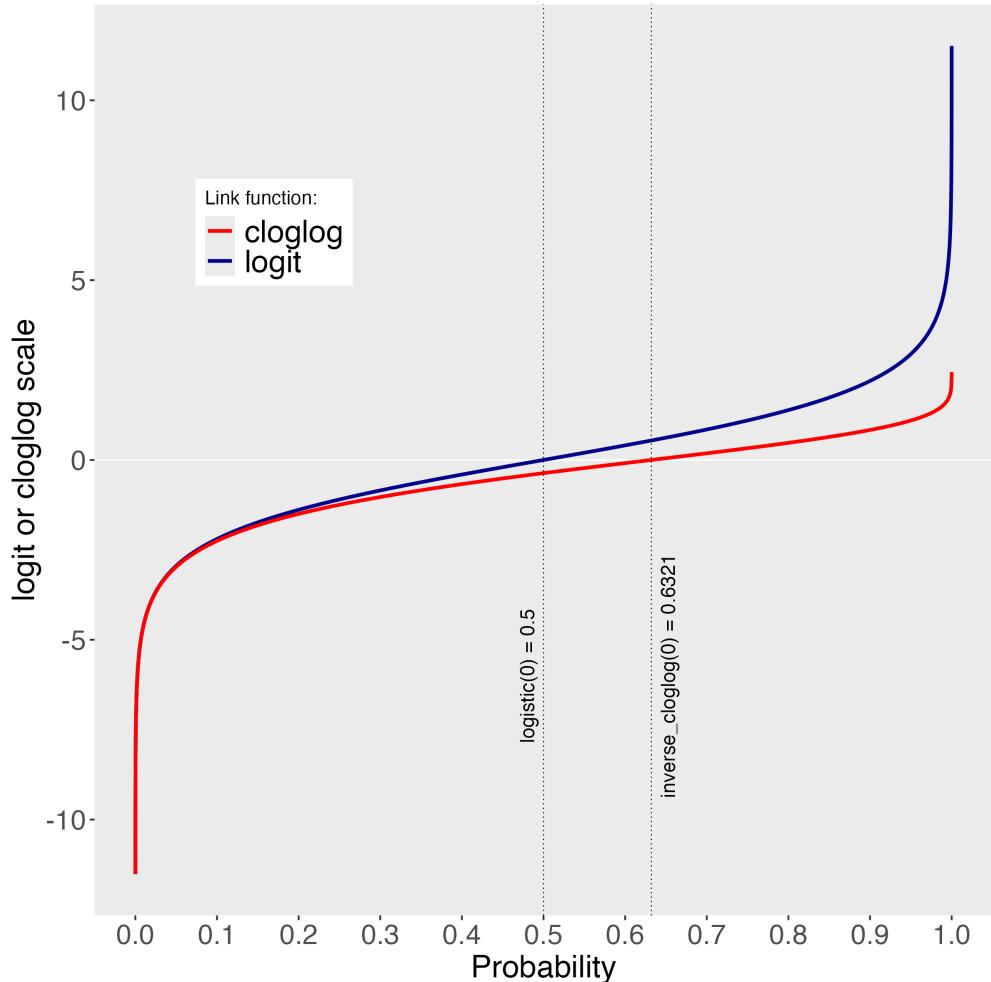


Figure 10. The logit and cloglog link functions.

₁₀₅₄ D. Regression equations

₁₀₅₅ An example (single-level) discrete-time hazard model with three predictors (TIME,
₁₀₅₆ X₁, X₂), the cloglog link function, and a third-order polynomial specification for TIME can

1057 be written as follows:

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

1060 The main predictor variable TIME is the time bin index t that is centered on value 9
1061 in this example. The first set of terms within brackets, the parameters β_0 to β_2 multiplied
1062 by their polynomial specifications of (centered) time, represents the shape of the baseline
1063 cloglog-hazard function (i.e., when all predictors X_i take on a value of zero). The second
1064 set of terms (the beta parameters β_3 to β_5) represents the vertical shift in the baseline
1065 cloglog-hazard for a 1 unit increase in the respective predictor variable. Predictors can be
1066 discrete, continuous, and time-varying or time-invariant. For example, the effect of a 1 unit
1067 increase in X_1 is to vertically shift the whole baseline cloglog-hazard function by β_1
1068 cloglog-hazard units. However, if the predictor interacts linearly with TIME (see X_2 in the
1069 example), then the effect of a 1 unit increase in X_2 is to vertically shift the predicted
1070 cloglog-hazard in bin 9 by β_2 cloglog-hazard units (when $\text{TIME}-9 = 0$), in bin 10 by $\beta_2 + \beta_3$ cloglog-hazard units (when $\text{TIME}-9 = 1$), and so forth. To interpret the effects of a
1072 predictor, its β parameter is exponentiated, resulting in a hazard ratio (due to the use of
1073 the cloglog link). When using the logit link, exponentiating a β parameter results in an
1074 odds ratio.

1075 An example (single-level) discrete-time hazard model with a general specification for
1076 TIME (separate intercepts for each of six bins, where D1 to D6 are binary variables
1077 identifying each bin) and a single predictor (X_1) can be written as follows:

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

1079 E. Prior distributions

1080 To gain a sense of what prior *logit* values would approximate a uniform distribution
1081 on the probability scale, Kurz (2023a) simulated a large number of draws from the

1082 Uniform(0,1) distribution, converted those draws to the log-odds metric, and fitted a
 1083 Student's t distribution. Row C in Figure 12 shows that using a t-distribution with 7.61
 1084 degrees of freedom and a scale parameter of 1.57 as a prior on the logit scale, approximates
 1085 a uniform distribution on the probability scale. According to Kurz (2023a), such a prior
 1086 might be a good prior for the intercept(s) in a logit-hazard model, while the N(0,1) prior in
 1087 row D might be a good prior for the non-intercept parameters in a logit-hazard model, as it
 1088 gently regularizes p towards .5 (i.e., a zero effect on the logit scale).

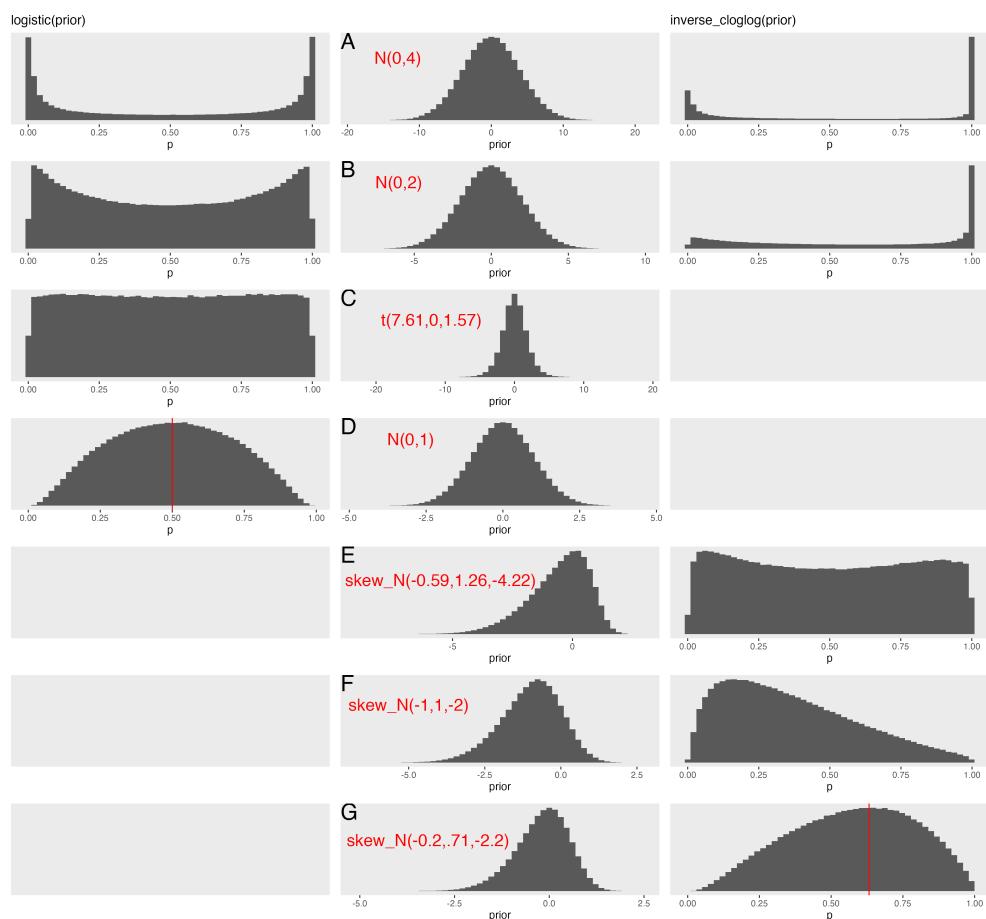


Figure 11. Prior distributions on the logit and/or cloglog scales (middle column), and their implications on the probability scale after applying the inverse-logit (or logistic) transformation (left column), and the inverse-cloglog transformation (right column).

1089 To gain a sense of what prior *cloglog* values would approximate a uniform distribution

on the hazard probability scale, we followed Kurz's approach and simulated a large number of draws from the Uniform(0,1) distribution, converted them to the cloglog metric, and fitted a skew-normal model (due to the asymmetry of the cloglog link function). Row E shows that using a skew-normal distribution with a mean of -0.59, a standard deviation of 1.26, and a skewness of -4.22 as a prior on the cloglog scale, approximates a uniform distribution on the probability scale. However, because hazard values below .5 are more likely in RT studies, using a skew-normal distribution with a mean of -1, a standard deviation of 1, and a skewness of -2 as a prior on the cloglog scale (row F), might be a good weakly informative prior for the intercept(s) in a cloglog-hazard model. A skew-normal distribution with a mean of -0.2, a standard deviation of 0.71, and a skewness of -2.2 might be a good weakly informative prior for the non-intercept parameters in a cloglog-hazard model as it gently regularizes p towards .6321 (i.e., a zero effect on the cloglog scale).

1102 F. Advantages of hazard analysis

1103 Statisticians and mathematical psychologists recommend focusing on the hazard
1104 function when analyzing time-to-event data for various reasons. First, as discussed by
1105 Holden, Van Orden, and Turvey (2009), "probability density [and mass] functions can
1106 appear nearly identical, both statistically and to the naked eye, and yet are clearly different
1107 on the basis of their hazard functions (but not vice versa). Hazard functions are thus more
1108 diagnostic than density functions" (p. 331) when one is interested in studying the detailed
1109 shape of a RT distribution (see also Figure 1 in Panis, Schmidt, et al., 2020). Therefore,
1110 when the goal is to study how psychological effects change over time, hazard and
1111 conditional accuracy functions are preferred.

1112 Second, because RT distributions may differ from one another in multiple ways,
1113 Townsend (1990) developed a dominance hierarchy of statistical differences between two
1114 arbitrary distributions A and B. For example, if $h_A(t) > h_B(t)$ for all t, then both hazard
1115 functions are said to show a complete ordering. Townsend (1990) concluded that stronger

conclusions can be drawn from data when comparing the hazard functions using EHA. For example, when mean A < mean B, the hazard functions might show a complete ordering (i.e., for all t), a partial ordering (e.g., only for $t > 300$ ms, or only for $t < 500$ ms), or they may cross each other one or more times.

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

₁₁₄₂ or computational models to data without studying the shape of the empirical discrete-time
₁₁₄₃ $h(t)$ and $ca(t)$ functions can miss important features in the data (Panis, Moran, et al.,
₁₁₄₄ 2020; Panis & Schmidt, 2016).