

Dependent t-test

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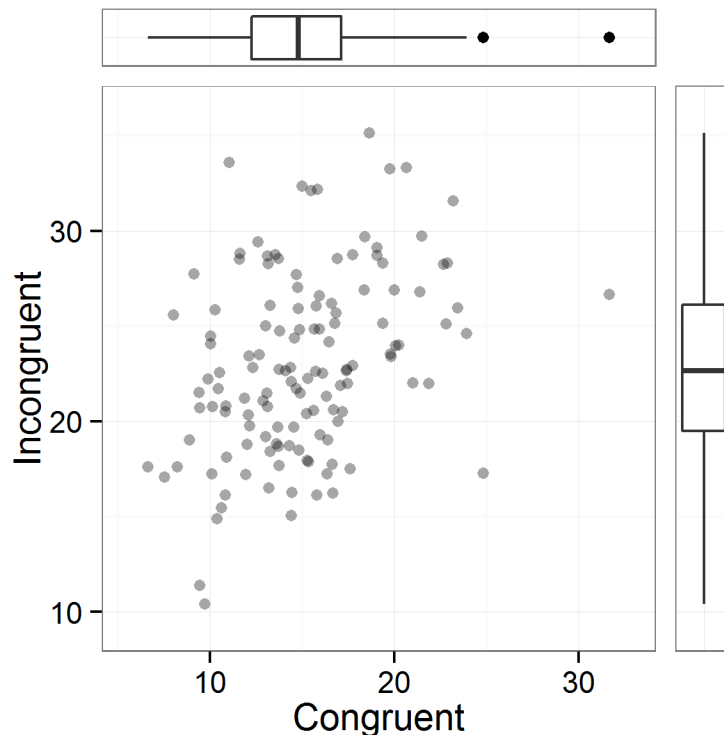
This document summarizes a comparison between two independent groups, comparing reaction times (in seconds) between the Congruent and Incongruent conditions. This script can help to facilitate the analysis of data, and the word-output might prevent copy-paste errors when transferring results to a manuscript.

Researchers can base their statistical inferences on Frequentist or robust statistics, as well as on Bayesian statistics. Effect sizes and their confidence intervals are provided, thus inviting researchers to interpret their data from multiple perspectives.

Checking for outliers, normality, equality of variances.

Outliers

Boxplots can be used to identify outliers. Boxplots give the median (thick line), and 25% of the data above and below the median (box). End of whiskers are the maximum and minimum value when excluding outliers (which are indicated by dots). Code adapted from [Sandy Muspratt](#).



Normality assumption

The dependent *t*-test assumes that *difference* scores are normally distributed and that the variances of the two groups are equal. It does *not* assume the data within each measurement (so within the Congruent and Incongruent condition) are normally distributed. If the normality assumption is violated, the Type 1 error rate of the test is no longer controlled, and can substantially increase beyond the chosen significance level. Formally, a normality test based on the data is incorrect, and the normality assumption should be tested on additional (e.g., pilot) data. Nevertheless, a two-step procedure (testing the data for normality, and using alternatives for the traditional *t*-test if normality is violated) works well (see [Rochon, Gondan, & Kieser, 2012](#)).

Tests for normality

[Yap and Sim \(2011, p. 2153\)](#) recommend: "If the distribution is symmetric with low kurtosis values (i.e. symmetric short-tailed distribution), then the D'Agostino-Pearson and Shapiro-Wilkes tests have good power. For symmetric distribution with high sample kurtosis (symmetric long-tailed), the researcher can use the JB, Shapiro-Wilkes, or Anderson-Darling test." The Kolmogorov-Smirnov (K-S) test is often used, but no longer recommended, and not included here.

If a normality test rejects the assumptions that the data is normally distributed (with $p < .05$) non-parametric or robust statistics have to be used (robust analyses are provided below).

The normality assumption was rejected in 0 out of 4 normality tests (Anderson-Darling, D'Agostino-Pearson, and Shapiro-Wilk).

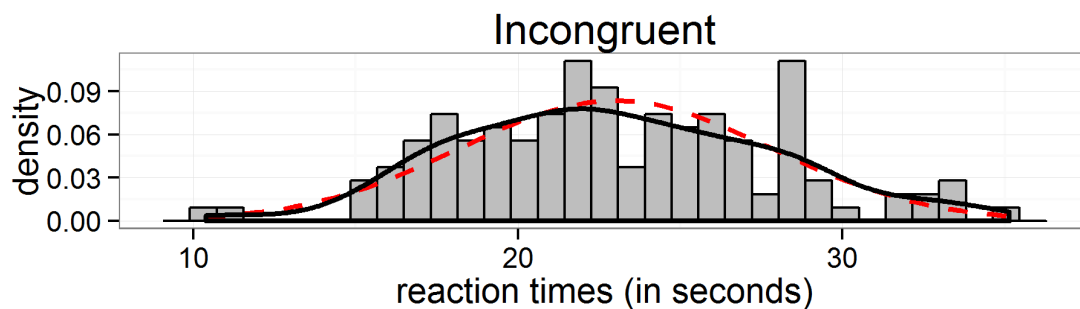
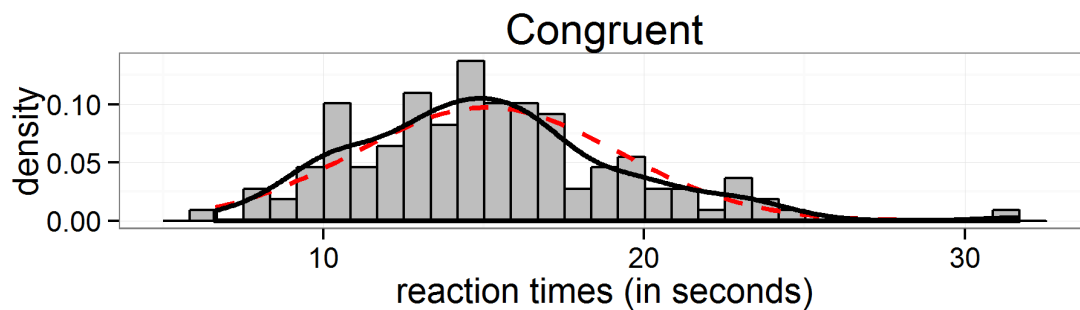
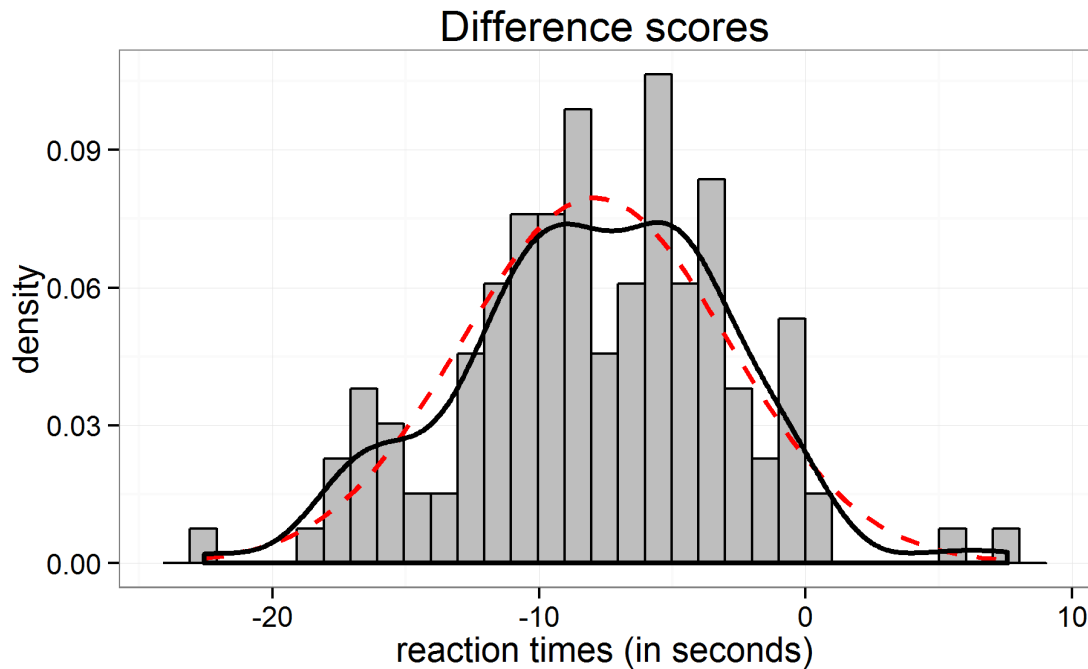
Test Name	<i>p</i> -value
Shapiro-Wilk	$p = 0.442$
D'Agostino-Pearson	$p = 0.627$
Anderson-Darling	$p = 0.333$
Jarque-Berra	$p = 0.765$

In very large samples (when the test for normality has close to 100% power) tests for normality can result in significant results even when data is normally distributed, based on minor deviations from normality. In very small samples (e.g., $n = 10$), deviations from normality might not be detected, but this does not mean the data is normally distributed. Always look at a plot of the data in addition to the test results.

Histogram, kernel density plot (black line) and normal distribution (red line) of difference scores

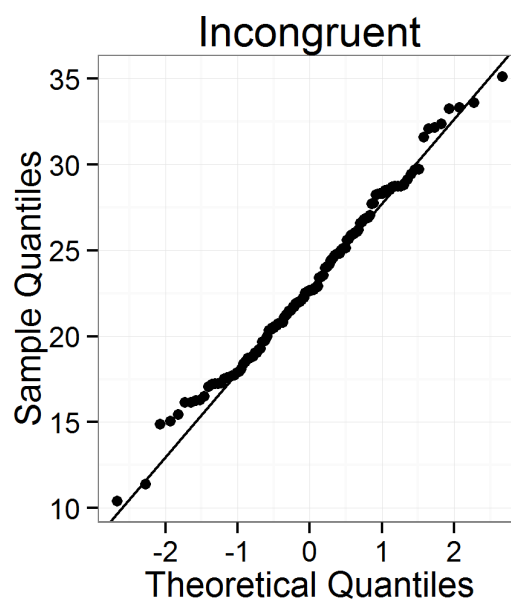
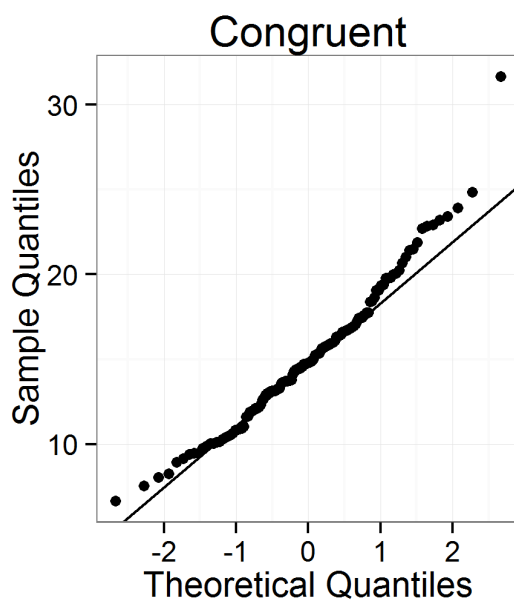
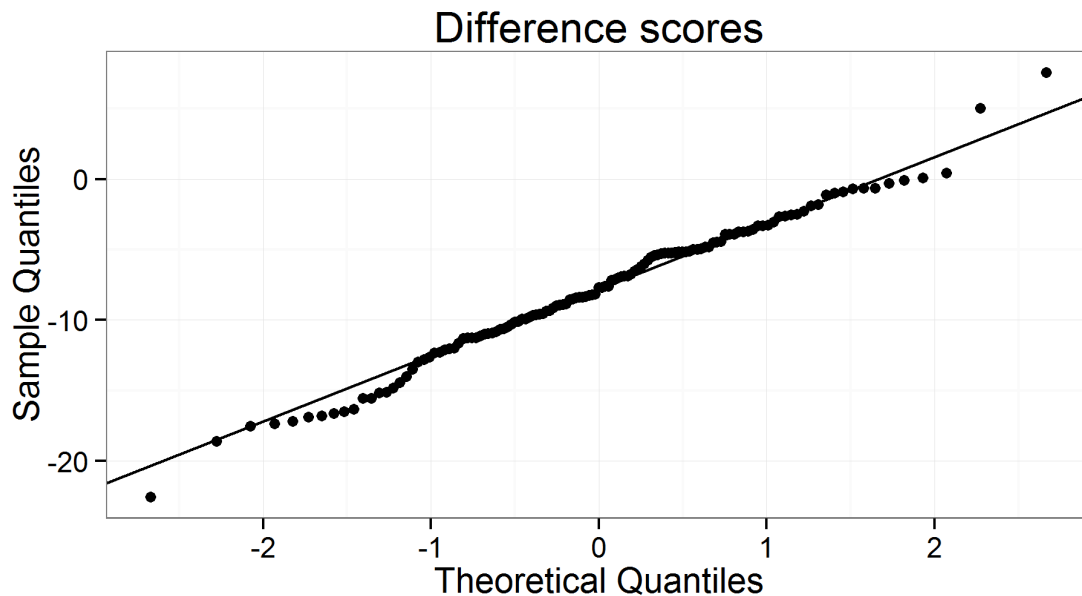
The density (or proportion of the observations) is plotted on the y-axis. The grey bars are a histogram of the difference scores. Judging whether data is normally distributed on the basis of a histogram depends too much on the number of bins (or bars) in the graph. A

kernel density plot (a non-parametric technique for density estimation) provides an easier way to check the normality of the data by comparing the shape of the density plot (the black line) with a normal distribution (the red dotted line, based on the observed mean and standard deviation). For dependent t-tests, the main DV is the *difference score*, and therefore the difference score should be normally distributed.



Q-Q-plot

In the Q-Q plot for the difference scores the points should fall on the line. Deviations from the line in the upper and lower quantiles indicates the tails of the distributions are thicker or thinner than in the normal distribution. An S-shaped curve with a dip in the middle indicates data is left-skewed (more values to the right of the distribution), while a bump in the middle indicates data is right-skewed (more values to the left of the distribution). For interpretation examples, see [here](#).



Equal variances assumption

In addition to the normality assumption, a second assumption of the t -test is that variances in both groups are equal. The variance is the standard deviation, squared, and the assumption is thus that the variance in the Congruent condition (16.81) equals that in the Incongruent condition (22.88). [Markowski & Markowski \(1990\)](#) show that if sample sizes are equal, violations of the equal variance assumption do not lead to unsatisfactory performance (defined as actual significance levels falling outside a 0.03-0.07 boundary for a nominal alpha level of 0.05).

Levene's test

This equality of variances assumption is typically examined with Levene's test, although in small samples, Levene's test can have low power, and thus fail to reject the null-hypothesis that variances are equal, even when they are unequal. Levene's test for equality of variances ($p = 0.038$) indicates that the assumption that variances are equal is rejected (consider reporting robust statistics).

Comparing the two sets of data

Frequentist statistics

A p -value is the probability of obtaining the observed result, or a more extreme result, assuming the null-hypothesis is true. It is not the probability that the null-hypothesis or the alternative hypothesis is true (for such inferences, see Bayesian statistics below). In repeated sampling, 95% of future 95% confidence intervals can be expected to contain the true population parameters (e.g, the mean difference or the effect size). Confidence intervals are not a statement about the probability that a single confidence interval contains the true population parameter, but a statement about the probability that future confidence intervals will contain the true population parameter. Hedges' g (also referred to as d_{unbiased} , see Borenstein, Hedges, Higgins, & Rothstein, 2009) is provided as best estimate of Cohen's d , but the best estimate of the confidence interval is based on d_{av} (as recommended by Cumming, 2012). Hedges's g and the 95% CI around the effect size are calculated using the MBESS package by [Kelley \(2007\)](#). The common language effect size expresses the probability that in any random pairing of two observations from both groups, the observation from one group is higher than the observation from the other group, see [McGraw & Wong, 1992](#). In a dependent t -test, the effect size Cohen's d can be calculated by using a standardizer that controls for the correlation between observations (d_{av}) or not (d_z). Both are provided, but d_{av} (or actually it's unbiased estimate, g_{av}) is recommended. For a discussion, see [Lakens, 2013](#). Default interpretations of the size of an effect as provided here should only be used as a last resort, and it is preferable to interpret the size of the effect in relation to other effects in the literature, or in terms of its practical significance.

Results

The mean reaction times (in seconds) ($M = 15.1$, $SD = 4.1$) of participants in the Congruent condition was smaller than the mean ($M = 23$, $SD = 4.78$) of participants in the Incongruent

condition ($r = 0.37$). The difference between measurements is ($M = -7.9$, $SD = 5.02$), 95% CI = $[-8.77; -7.04]$, $t(130) = -18.04$, $p < 0.001$, Hedges' $g = -1.76$, 95% CI $[-2.06; -1.48]$ (or $d_z = -1.58$, 95% CI $[-1.83; -1.32]$). This can be considered a large effect. The observed data is surprising under the assumption that the null-hypothesis is true. The Common Language effect size (McGraw & Wong, 1992) indicates that after controlling for individual differences, the likelihood that a persons reaction times (in seconds) in the Congruent condition is smaller than the reaction times (in seconds) in the Incongruent condition is 94%.

Bayesian statistics

Bayesian statistics can quantify the relative evidence in the data for either the alternative hypothesis or the null hypothesis. Bayesian statistics require priors to be defined. In the Bayes Factor calculation reported below, a non-informative Jeffreys prior is placed on the variance of the normal population, while a Cauchy prior is placed on the standardized effect size (for details, see [Morey & Rouder, 2011](#)). Calculations are performed using the [BayesFactor package](#). Default interpretations of the strength of the evidence are provided but should not distract from the fact that strength of evidence is a continuous function of the Bayes Factor. A second popular Bayesian approach relies on estimation, and the mean posterior and 95% highest density intervals (HDI) are calculated following recommendations by [Kruschke, \(2013\)](#) based on vague priors. According to Kruschke (2010, p. 34): 'The HDI indicates which points of a distribution we believe in most strongly. The width of the HDI is another way of measuring uncertainty of beliefs. If the HDI is wide, then beliefs are uncertain. If the HDI is narrow, then beliefs are fairly certain.' To check the convergence and fit of the HDI simulations, the Brooks-Gelman-Rubin scale reduction factor for the difference score should be smaller than 1.1 (it is 1.0000365) and the effective sample size should be larger than 10000 (it is 62718). Thus, the HDI simulation is acceptable.

Results

The JZS BF_{10} (with r scale = 0.5) = 5.820268510^{33} . This indicates the data are 5.820268510^{33} (or $\log_e BF = 77.75$) times more probable under the alternative hypothesis, than under the null hypothesis. This data provides decisive evidence for H1. The posterior mean difference is -7.88, 95% HDI = $[-8.75; -7.01]$.

Robust statistics

Values in the tails of the distribution can have a strong influence on the mean. If values in the tails differ from a normal distribution, the power of a test is reduced and the effect size estimates are biased, even under slight deviations from normality (Wilcox, 2012). One way to deal with this problem is to remove the tails in the analysis by using *trimmed means*. A recommended percentage of trimming is 20% from both tails (Wilcox, 2012), which means inferences are based on the 60% of the data in the middle of the distribution. Yuen's method can be used to compare trimmed means (when the percentage of trimming is 0%, Yuen's method reduces to Welch's t -test). The equivalent of Cohen's d for within designs is not yet available, so the explanatory effect size is reported ([Wilcox & Tian, 2011](#)).

Explanatory power (ξ , replace in the output below by the Greek lowercase ξ symbol) is the robust equivalent of omega squared (unbiased eta squared, or r squared), and thus related to d_z in size, not to d_{av} . The effect size convention of small, medium, and large corresponds approximately to $\xi = 0.15$, 0.35 and 0.50 .

Results

Using the Yuen-Welch method for comparing 20% trimmed means showed the mean difference in reaction times (in seconds) between conditions is ($M = -8.01$, 95% CI $[-8.04; -7.98]$), which is statistically different from zero, $t(78) = -16.91$, $p < 0.001$, $\xi = -1.67$. The observed data is surprising under the assumption that the null-hypothesis is true. This can be considered a large effect.

Plotting data

Graph examples. In the code, you can turn different layers on and off, and change their properties by adding or removing # in front of a line of code. Displays violin plot (rotated kernel density plots) and 95% CI bars (for between designs and adjusted for within designs following Morey (2008)), individual data-points, or simple bar graphs.

Figure 1. Means, violin plot, and two-tiered 95% within (crossbars) and between (endpoints of lines) confidence intervals following Baguley (2012), and violin plot.

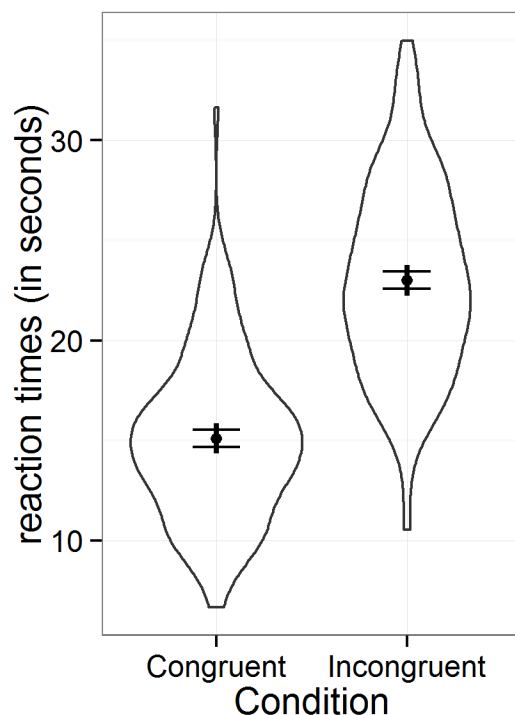


Figure 2. Means, datapoints, and 95% CI (between & within)

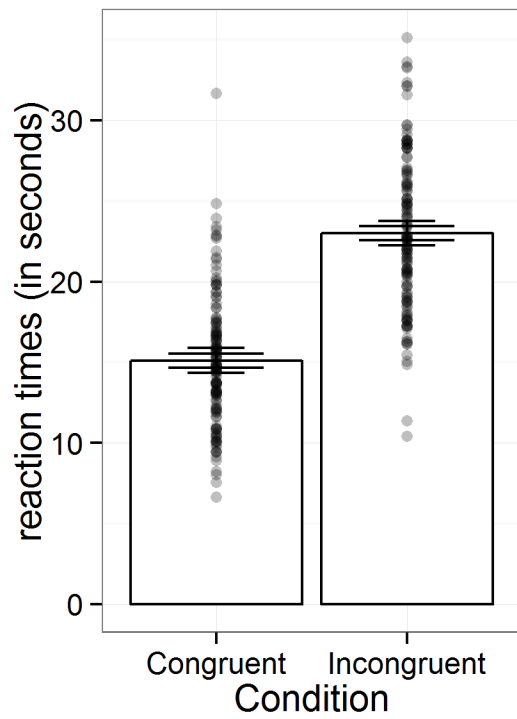
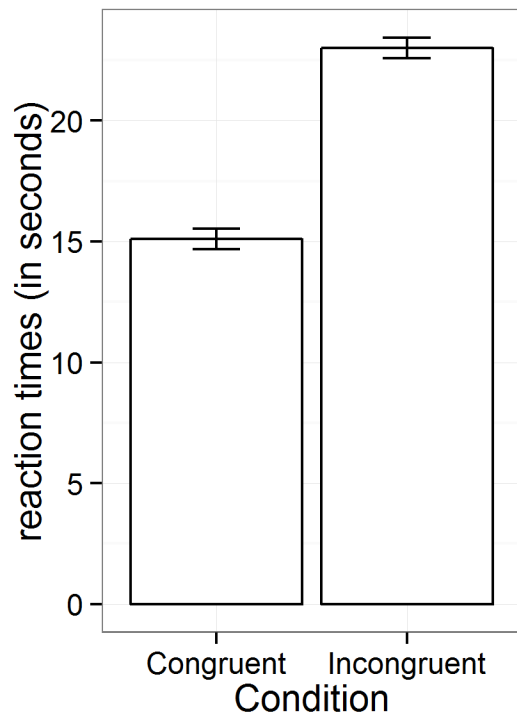


Figure 3. Bar chart displaying means and 95% CI (between)



References

This script uses the *reshape2* package to convert data from wide to long format, the *PowerR* package to perform the normality tests, *HLMdiag* to create the QQplots, *ggplot2* for all plots, *gtable* and *gridExtra* to combine multiple plots into one, *car* to perform Levene's test, *MBESS* to calculate effect sizes and their confidence intervals, *WRS* for the robust statistics, *BayesFactor* for the bayes factor, and *BEST* to calculate the Bayesian highest density interval.

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Appendix A: Data & Session Information

alldata

##	PPNR	Congruent	Incongruent	Year	diff
## 1	1	21.871	21.974	2013	-0.103
## 2	2	22.820	25.116	2013	-2.296
## 3	3	14.810	18.500	2013	-3.690
## 4	4	10.142	20.786	2013	-10.644
## 5	5	14.414	22.097	2013	-7.683
## 6	6	19.803	23.402	2013	-3.599
## 7	7	9.881	22.212	2013	-12.331
## 8	8	15.939	24.833	2013	-8.894
## 9	9	9.457	11.374	2013	-1.917
## 10	10	8.230	17.616	2013	-9.386
## 11	11	21.490	29.729	2013	-8.239
## 12	12	16.300	21.300	2013	-5.000
## 13	13	14.700	27.704	2013	-13.004
## 14	14	11.600	28.500	2013	-16.900
## 15	15	16.765	25.133	2013	-8.368
## 16	16	12.890	21.077	2013	-8.187
## 17	17	12.081	20.331	2013	-8.250
## 18	18	17.439	22.710	2013	-5.271
## 19	19	15.666	24.837	2013	-9.171
## 20	20	18.399	29.679	2013	-11.280
## 21	21	17.063	21.878	2013	-4.815
## 22	22	16.096	22.528	2013	-6.432
## 23	23	10.628	15.449	2013	-4.821
## 24	24	14.381	22.821	2013	-8.440
## 25	25	13.785	24.727	2013	-10.942
## 26	26	11.038	33.600	2013	-22.562
## 27	27	15.315	22.254	2013	-6.939
## 28	28	17.739	22.917	2013	-5.178
## 29	29	24.825	17.259	2013	7.566
## 30	30	20.065	23.970	2013	-3.905
## 31	31	13.137	20.761	2013	-7.624
## 32	32	13.552	28.738	2013	-15.186
## 33	33	13.121	28.694	2013	-15.573
## 34	34	12.324	22.832	2013	-10.508
## 35	35	6.636	17.598	2013	-10.962
## 36	36	15.469	32.099	2013	-16.630
## 37	37	15.967	19.289	2013	-3.322
## 38	38	14.543	19.697	2013	-5.154
## 39	39	16.332	17.231	2013	-0.899
## 40	40	15.347	17.871	2013	-2.524
## 41	41	14.984	32.352	2013	-17.368
## 42	42	15.809	16.130	2013	-0.321
## 43	43	14.106	22.661	2013	-8.555
## 44	44	19.774	23.533	2013	-3.759
## 45	45	13.200	16.500	2013	-3.300

## 46	46	13.701	28.526	2013	-14.825
## 47	47	15.274	17.935	2013	-2.661
## 48	48	14.743	27.036	2013	-12.293
## 49	49	8.032	25.590	2013	-17.558
## 50	50	11.931	17.201	2013	-5.270
## 51	51	20.664	33.328	2013	-12.664
## 52	52	13.260	18.410	2013	-5.150
## 53	53	23.417	25.966	2013	-2.549
## 54	54	13.146	28.276	2013	-15.130
## 55	55	10.031	24.467	2013	-14.436
## 56	56	16.941	19.983	2013	-3.042
## 57	57	10.843	20.492	2013	-9.649
## 58	58	11.631	28.823	2013	-17.192
## 59	59	9.128	27.731	2013	-18.603
## 60	60	10.870	20.802	2013	-9.932
## 61	61	16.601	26.202	2013	-9.601
## 62	62	12.657	23.506	2013	-10.849
## 63	63	7.525	17.075	2013	-9.550
## 64	64	23.919	24.615	2013	-0.696
## 65	65	10.375	14.871	2013	-4.496
## 66	66	13.743	17.680	2013	-3.937
## 67	67	17.405	22.651	2013	-5.246
## 68	68	10.442	21.725	2013	-11.283
## 69	69	8.900	19.034	2013	-10.134
## 70	70	13.700	18.700	2013	-5.000
## 71	71	13.671	19.681	2013	-6.010
## 72	72	12.598	29.429	2013	-16.831
## 73	73	14.908	21.464	2013	-6.556
## 74	74	19.352	25.129	2013	-5.777
## 75	75	19.359	28.297	2013	-8.938
## 76	76	19.997	26.881	2013	-6.884
## 77	77	20.237	24.007	2013	-3.770
## 78	78	16.648	16.238	2013	0.410
## 79	79	14.412	15.064	2013	-0.652
## 80	80	31.669	26.643	2013	5.026
## 81	81	14.286	18.714	2013	-4.428
## 82	82	12.110	23.431	2013	-11.321
## 83	83	13.619	18.830	2013	-5.211
## 84	84	13.741	22.715	2014	-8.974
## 85	85	14.788	25.916	2014	-11.128
## 86	86	16.819	25.677	2014	-8.858
## 87	87	11.888	21.213	2014	-9.325
## 88	88	10.516	22.556	2014	-12.040
## 89	89	9.436	20.715	2014	-11.279
## 90	90	13.256	26.072	2014	-12.816
## 91	91	18.643	35.135	2014	-16.492
## 92	92	15.827	32.161	2014	-16.334
## 93	93	13.000	25.000	2014	-12.000
## 94	94	17.600	17.513	2014	0.087
## 95	95	19.065	28.724	2014	-9.659

```
## 96      96      16.387      19.028 2014 -2.641
## 97      97      19.765      33.259 2014 -13.494
## 98      98      10.281      25.849 2014 -15.568
## 99      99      16.702      20.620 2014 -3.918
## 100     100      17.465      21.981 2014 -4.516
## 101     101      19.040      29.129 2014 -10.089
## 102     102      22.678      28.249 2014 -5.571
## 103     103      15.767      26.069 2014 -10.302
## 104     104      14.445      16.273 2014 -1.828
## 105     105      16.888      28.540 2014 -11.652
## 106     106      10.034      24.069 2014 -14.035
## 107     107      10.091      17.241 2014 -7.150
## 108     108      16.460      24.180 2014 -7.720
## 109     109      15.721      22.622 2014 -6.901
## 110     110      10.900      18.100 2014 -7.200
## 111     111      17.196      20.492 2014 -3.296
## 112     112      21.392      26.789 2014 -5.397
## 113     113      17.725      28.750 2014 -11.025
## 114     114      23.204      31.584 2014 -8.380
## 115     115      15.926      26.590 2014 -10.664
## 116     116      16.618      17.744 2014 -1.126
## 117     117      14.850      24.800 2014 -9.950
## 118     118      13.003      19.204 2014 -6.201
## 119     119      15.247      20.389 2014 -5.142
## 120     120       9.396      21.525 2014 -12.129
## 121     121      11.998      18.776 2014 -6.778
## 122     122      15.615      20.585 2014 -4.970
## 123     123      22.891      28.302 2014 -5.411
## 124     124      10.825      16.130 2014 -5.305
## 125     125      14.690      21.712 2014 -7.022
## 126     126      21.000      22.000 2014 -1.000
## 127     127      18.363      26.899 2014 -8.536
## 128     128       9.733      10.396 2014 -0.663
## 129     129      14.563      24.382 2014 -9.819
## 130     130      12.162      19.769 2014 -7.607
## 131     131      13.076      21.463 2014 -8.387
```

```
sessionInfo()
```

```
## R version 3.2.0 (2015-04-16)
## Platform: x86_64-w64-mingw32/x64 (64-bit)
## Running under: Windows 8 x64 (build 9200)
##
## locale:
## [1] LC_COLLATE=Dutch_Netherlands.1252 LC_CTYPE=Dutch_Netherlands.1252
## [3] LC_MONETARY=Dutch_Netherlands.1252 LC_NUMERIC=C
## [5] LC_TIME=Dutch_Netherlands.1252
##
## attached base packages:
## [1] grid      parallel stats      graphics grDevices utils      datasets
```

```
## [8] methods    base
##
## other attached packages:
##  [1] BEST_0.2.2          rjags_3-15          BayesFactor_0.9.11-1
##  [4] coda_0.17-1         MASS_7.3-40         WRS_0.27.5
##  [7] MBESS_3.3.3         car_2.0-25          gridExtra_0.9.1
## [10] gtable_0.1.2        ggplot2_1.0.1       HLMdiag_0.2.5
## [13] lme4_1.1-7          Matrix_1.2-0        Power_1.0.4
## [16] Rcpp_0.11.6         reshape2_1.4.1
##
## loaded via a namespace (and not attached):
##  [1] formatR_1.2          nloptr_1.0.4        plyr_1.8.2
##  [4] tools_3.2.0          digest_0.6.8        evaluate_0.7
##  [7] nlme_3.1-120         lattice_0.20-31     mgcv_1.8-6
## [10] yaml_2.1.13          mvtnorm_1.0-2       SparseM_1.6
## [13] proto_0.3-10         stringr_1.0.0       knitr_1.10
## [16] MatrixModels_0.4-0   gtools_3.4.2        stats4_3.2.0
## [19] nnet_7.3-9           pbapply_1.1-1       rmarkdown_0.5.1
## [22] minqa_1.2.4          magrittr_1.5         scales_0.2.4
## [25] htmltools_0.2.6      splines_3.2.0       pbkrtest_0.4-2
## [28] colorspace_1.2-6     labeling_0.3         quantreg_5.11
## [31] stringi_0.4-1        munsell_0.4.2
```

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