Cognitive architecture and capacity of the cognitive system responsible for *Same* – *Different* judgments

Marc-André Goulet¹ · Denis Cousineau¹

Published online: 9 March 2020
© The Psychonomic Society, Inc. 2020

Abstract

Participants tend to match identical pairs of stimuli faster than different pairs. Despite many endeavours to explain this *fast-same effect*, there is still no theoretical consensus. A potential reason for the lack of consensus is that the cognitive architecture and capacity underlying such phenomenon is assumed and not formally tested. For example, the dual-process approach suggests that *Same* responses arise from a parallel treatment, whereas *Different* responses arise from a serial treatment. It also suggests that in both conditions, the capacity of the process is unaffected by workload (*unlimited capacity*). Alternative approaches argue that the fast-same effect can be explained by parallel or coactive architectures with channels working in either limited or super capacity. In this study, we formally assess the architecture (three possibilities: serial, parallel and coactive) and the capacity (three possibilities: unlimited, limited and super-capacity) of the cognitive system in a *Same-Different* task using Systems Factorial Technology (SFT). We recruited twenty participants to perform a double-factorial task lasting four sessions. Because of the lack of effectiveness of the blurring manipulation, we cannot draw a strong conclusion about the cognitive architecture. As for the capacity, the results show that it is mostly limited for the majority of participants. However, between 300 and 500 ms, participants tend to have a much stronger processing capacity in the *Same* condition compared to the *Different* condition. This short but strong burst of activity for identical stimuli might explain the fast-same effect.

Keywords Same-different judgments · Cognitive architecture · Cognitive capacity · Systems factorial technology

The assessment of similarity and differences in objects is a basic cognitive behaviour performed daily. Typically, this ability is studied by presenting pairs of stimuli to participants whose task is to indicate if the stimuli are *Same* or *Different*. One intriguing result of such a task is that participants respond quicker in *Same* trials compared to *Different* trials (e.g., Bamber, 1969; Egeth, 1966; Nickerson, 1965; Posner & Mitchell, 1967). This result contradicts a first intuitive theory to explain similarity judgment in which identifying a *Same* pair requires an exhaustive treatment of all the stimulus's attributes. On the other hand, a *Different* pair only requires the identification of one mismatching attribute. Therefore, this theory posits that participants would respond faster in the *Different* trials.

This theoretical approach has its origin in the visual search literature. In this task, participants must identify a target among distractors (Holmgren, Juola, & Atkinson, 1974). As soon as the participant identifies the target, they have enough information to respond, but in trials without targets, the search must be exhaustive and process all the distractors before concluding that there is no target. This strategy was explored in the *Same-Different* task with what was dubbed *disjunctive tasks* in which participants are asked to detect the presence of any matching attribute between two stimuli (Bamber, Herder, & Tidd, 1975; Derks, 1972; Farell, 1977; Nickerson, 1967a; Sekuler & Abrams, 1968; Silverman & Goldberg, 1975; Taylor, 1976). In the disjunctive task, participants must find at least one matching attribute to respond *Same*. The results of such task show an inversely proportional relationship between the number of critical attributes (the number of matches) and the response time. Symmetrically, in the classical versions of the *Same-Different* task (the *conjunctive task*), participants must detect at least one mismatching attribute to respond *Different* (Farell, 1985; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009). If the symmetry was perfect,

✉ Marc-André Goulet
mgoul101@uottawa.ca

¹ School of Psychology, University of Ottawa, 136 Jean-Jacques Lussier, Ottawa K1N 6N5, Canada

one would expect that in the conjunctive task, the slowest condition would be the *Same* condition (the one with zero critical attributes). However, in such task, the opposite is observed: the *Same* condition is the fastest.

Many experiments explored the fast-same effect by manipulating the stimuli (mainly letters and geometric shapes; see Bamber, 1969; Nickerson, 1967a, b; but also line lengths, tones and motion directions; see Bindra, Donderi, & Nishisato, 1968; Bindra, Williams, & Wise, 1965; Link & Tindall, 1971; Petrov, 2009) and the design / instructions (Proctor & Rao, 1983b; Proctor, Rao, & Hurst, 1984; Ratcliff & Hacker, 1981; Taylor, 1977). Yet, as spelled out in the many review articles on the effect, there is no consensus on why this phenomenon occurs (Farell, 1985; Krueger, 1978; Luce, 1986; Nickerson, 1973, 1978; Ratcliff, 1985; Sternberg, 1998).

A main reason for the lack of consensus is that these theoretical explanations are not, in most cases, framed in terms of the cognitive architecture and capacity of the cognitive system underlying the task. Most theoretical explorations focused on questions regarding variations on decision thresholds, encoding rates and evidence accumulation rates. However, they disregarded how the process of evidence accumulation is implemented. Indeed, most investigations on the fast-same effect occurred prior to the publication of Townsend's methodology for diagnosing cognitive architecture and capacity (Townsend & Ashby, 1983; Townsend & Nozawa, 1995). This *taxonomy of elementary cognitive processes* was not ignored; most of the explanations supposed a specific organization of the processing channels. However, the architecture underlying these theories were not formally tested, simply assumed.

The objective of this study is twofold: to formally assess 1) the cognitive architecture and 2) the capacity of the cognitive system responsible for *Same* and *Different* judgments. We focus on how evidences are accumulated (i.e., one at a time, in parallel or collaboratively) and how the cognitive processes respond to an increase in the total amount of information presented (i.e., are they unaffected, hindered or facilitated?). Although these research questions do not directly address potential variations in thresholds, encoding rates and evidence accumulation rates, it will provide a more solid framework to model these parameters.

Cognitive architectures

In a seminal paper on the *Same-Different* task, Bamber (1969) proposed that two processes are involved in the response. The first processor is an *identity reporter* which processes a chunked version of the stimulus to detect solely similarity. The processing units (or *channels*) of the identity reporter are assumed to be organized in parallel so that all the attributes

are processed simultaneously. The second processor, responsible for *Different* responses, is analytical: it partitions the stimulus in many attributes for a thorough treatment (Nickerson, 1965). This slower treatment of the attributes would be more apt at distinguishing a mismatch from a match in the presence of internal noise. As mentioned by Krueger (1978), it is more likely that noise changes a matching attribute into a mismatching attribute than the opposite. For example, a participant is presented with a “J” followed by a “T”. Due to internal noise, it is possible that the second stimulus is truly a “J” that has been perceived as a “T”. Therefore, the participant should process this stimulus more thoroughly to confidently say that it is mismatching. Conversely, if the participant perceives the second stimulus as a “J”, because the probability that a mismatching letter is transformed into a “J” is low, the participant can confidently say that it is matching. For this reason, participants might process mismatching attributes more thoroughly to ensure accurate responses. It is also assumed in Bamber (1969) that the comparisons are performed serially. The attributes are processed one by one and as soon as a mismatching attribute is detected, the treatment is terminated. This conceptualization adequately accounts for the decrease in response time (RT) when the number of mismatches increases (Bamber, 1969; Egeth, 1966; Nickerson, 1967b).

Alternatively, some researchers have argued that *Different* RTs can also be modelled with a parallel architecture (Hawkins, 1969; Hawkins & Shigley, 1972). These authors showed that if the channels have different processing rates, a parallel model can fit the relationship between RT and the number of mismatches. Studies manipulating the position of the mismatching attributes show evidence for discrepancies in channels processing rates, where attributes located at the extremities of the stimulus are processed faster than attributes located at the centre (Howell & Stockdale, 1975; Koriart & Norman, 1989a, b; Proctor, Healy, & Van Zandt, 1991).

Serial and parallel architectures posit that each channel can trigger responses independently of the other channels. On the other hand, the coactive architecture, proposed by Miller (1978, 1982), postulate that the role of the channels is to feed their activation to a single counting unit (an accumulator) which is responsible for responding. Therefore, the channels are working in collaboration: they pool their evidence until the counting unit's decision threshold is reached for either response alternative.

As seen, the assumed underlying architecture changes how one theoretically explains the fast-same effect. When the serial architecture is assumed, the fast-same effect seems to be the result of a criterion shift, that is, to be caused by discrepancies in decision thresholds. On the other hand, when the parallel architecture is assumed, the fast-same effect seems to be the results of varying evidence accumulation rates. Finally, when a coactive architecture is assumed, the fast-same effect seems

to be the results of the architecture itself, and not caused by variations of specific theoretical parameters.

Despite its central role, architectural questions have been omitted by a few more models that posit single-process explanations. These models focused mainly on the accumulation of information over time. They proposed that the fast-same effect can be the result of encoding facilitation (Eriksen, O'Hara, & Eriksen, 1982; Krueger, 1978, 1983; Proctor, 1981, 1986; Proctor & Rao, 1983a; St. James & Eriksen, 1992) or response bias for *Same* (Irwin, Hautus, & Francis, 2001; Ratcliff, 1978; Ratcliff & Hacker, 1981; Ratcliff, McKoon, & Verwoerd, 1989; Taylor, 1977). These models likely assumed that the information is gathered in parallel, and that the number of attributes contained in the stimuli has no effect on the processing efficiency (this is also referred to as unlimited capacity, independent parallel – UCIP).

Capacity of the system

Like cognitive architecture, the capacity of the cognitive system has never been tested directly in the *Same-Different* task. Capacity relates to the efficiency of the treatment when the number of attributes – the workload – is increased (Hylan, 1903). In such scenario, the processing efficiency might remain unchanged (*unlimited capacity*) but might also be hindered (*limited capacity*) or augmented (*super capacity*). As put by Eidels, Houpt, Altieri, Pei, and Townsend (2011), the capacity of a system characterizes whether additional information facilitates or inhibits the system irrespective of the number of processes assumed.

The most commonly found assumption is that the efficiency of the cognitive system is unlimited – that the workload does not facilitate nor inhibit the processing time. This assumption has not been directly tested within the *Same-Different* task. Assuming by default that the capacity is unlimited can lead to important theoretical misconceptions. For example, a common result of the *Same-Different* task is that increasing the number of attributes slows down the response time (Atkinson, Holmgren, & Juola, 1969; Bamber, 1969; Sternberg, 1966). If processing capacity is unaffected by an increased number of attributes, the slowdown in response time would likely be caused by greater decision thresholds (as more information needs to be processed). However, if the capacity is affected, the discrepancy in response time can be explained by differences in processing rate (Donkin, Little, & Houpt, 2014).

A few authors proposed that the capacity of the channels might indeed be limited in the *Same-Different* task (Decker, 1974; Hawkins & Shigley, 1972; Link & Tindall, 1971). However, their proposal was deduced from comparing mean RTs across conditions. Mean RTs can lead to erroneous assumptions regarding cognitive architecture (Godwin,

Walenchok, Houpt, Hout, & Goldinger, 2015; Little, Eidels, Houpt, & Yang, 2017; Townsend, 1972). For example, mean RTs cannot distinguish between the time required to perform subtasks in a serial architecture and the time required by each processing channels in a parallel architecture (*intercompletion times* – Townsend, 1972). For this reason, Townsend and Nozawa (1995), among others, suggested using a factorial design and comparing distributions of RTs across conditions instead. Similarly, distributions can be used to gather information regarding the processing capacity of the channels (i.e., Grice, Canham, & Gwynne, 1984; Miller, 1982).

The aforementioned work of Miller (1978, 1982) used distributions of RTs to support not only the coactive architecture but also the super-capacity workload of the system. This is, however, the only study supporting super-capacity in the *Same-Different* task.

Formal assessment of architecture and capacity

Architecture and capacity questions were assumed in past theoretical endeavours to explain the fast-same phenomenon. About any architecture and any capacity have been assumed (see summary in Table 1). The proposed study is therefore an opportunity to falsify a large number of candidate models. In this study, we formally assess the architecture and the capacity of the cognitive system in the *Same-Different* task.

These two research questions can be directly addressed using Systems Factorial Technology (SFT; Townsend & Nozawa, 1995; but also see Harding et al., 2016; Little, Altieri, Fifić, & Yang, 2017). It combines Donders (1969)'s subtractive and Sternberg (1969)'s additive methods to derive architectural information using the entire distribution of RTs instead of the mean RT.

SFT requires a double-factorial design, that is, an experimental manipulation involving two attributes. In a seminal example, the participants are asked to detect the presence of any dot on a computer display (Townsend & Nozawa, 1995). The dot can be on the left part of the screen (attribute 1) or on the right part of the screen (attribute 2). Participants were asked to press an answer key if at least one dot was presented on the screen, and another answer key if no dot was presented. Each dot can either be clear (high perceptibility - H) or barely visible (low perceptibility - L). The four possible experimental conditions (HH, HL, LH and LL) are then used to diagnose the architecture of the processing channels. The first manipulated factor concerns the number of attributes displayed on the screen. The second manipulated factor is the saliency of the attributes.

In order to diagnose the capacity of the cognitive system, the double-factorial design is expanded with four additional conditions, in which only one attribute is displayed on the

screen (HX, LX, XH and XL, where X denotes a missing attribute). It is technically possible to have a ninth condition in which no stimulus is displayed on the screen. However, since it does not directly address our research questions, we omit this empty condition in the current study (Houpt, Blaha, McIntire, Havig, & Townsend, 2014).

SFT has three assumptions. First, the manipulation must have a *selective influence* on the attributes. In the Townsend and Nozawa's (1995) dot experiment, the clarity of the leftmost dot must not influence the clarity of the rightmost dot. This assumption is critical to interpret interaction contrasts (Sternberg, 1969). In the present study, we used the *mean interaction contrast* (MIC) and the *survivor interaction contrast* (SIC) described in Appendix A.

Second, to interpret capacity, we must assume *context invariance* whereby the processing rate of each processing channel is not influenced by the total number of attributes in a condition (Ashby & Townsend, 1986; Houpt et al., 2014; Townsend & Eidels, 2011; Townsend, Houpt, & Silbert, 2012; Yang, Altieri, & Little, 2018). In more technical terms, the mean (or the variance) processing competition time of a channel processing a single attribute must not differ between conditions in which only this attribute is present, and condition in which other attributes are also present. Context invariance is required to interpret the capacity coefficient of the system.

Third, SFT postulates that the channels responsible for processing information are stochastically independent (Heathcote, Brown, & Cousineau, 2004; Townsend & Nozawa, 1995). In other words, the processing rate of a channel must not be correlated with the processing rate of other channels. There exists stochastic dependency when the system allows cross-talk between the processing channels (Mordkoff & Yantis, 1991). Although the vast majority of models of the Same-Different task posit stochastic independence, cross-talk has been proposed as a potential explanation for the fast-same phenomenon (Eriksen et al., 1982). Recent work has shown that in cases of stochastic dependency, SFT can still be used to assess the type of channel dependency (inhibitory, facilitatory or both – Eidels et al., 2011).

With this expanded double-factorial design, we can compute the MIC, which distinguishes serial architectures from

parallel and coactive architectures, and the SIC, which distinguishes between all three architectures, and the *capacity coefficient*, which can assess processing capacity. Appendix A expands on these measures and their interpretability.

In the current study, we use the expanded double-factorial design and SFT to directly assess our two main research questions. First, we diagnose the architecture of cognitive system responsible to make *Same* and *Different* judgments. There are three possible outcomes: the architecture could be serial, parallel or coactive. Second, we assess the effect of the workload on the capacity of the system. Again, there are three possible outcomes: the capacity could be unlimited, limited or super-capacity.

Methods

The experiment consisted in a mix between a classical Same-Different Task design (e. g., Bamber, 1969) and Townsend and Nozawa (1995)'s double-factorial design, expanded as per Houpt et al. (2014). Instead of a target present / target absent task, as in Townsend and Nozawa (1995), participants need to indicate whether two arrays composed of one or two letters presented in succession are *Same* or *Different*. The leftmost and the rightmost letters of the second stimulus of the pair are subject to the clarity manipulation of the double-factorial design. In conditions where only one letter is displayed, the participants are asked to ignore the missing attribute. In addition to the clarity manipulation, we also manipulated the identity of the arrays, that is whether they are *Same* or *Different*. In *Same* trials, all the attributes are matching, whereas in *Different* trials, all the attributes are mismatching.

Participants and power analysis

The participants were twenty undergraduate and graduate students of the University of Ottawa recruited by the experimenter. Upon the completion of the task, the participants received \$50 CAD. This experimental protocol was approved by the University of Ottawa's Research Ethics Board.

Table 1 Overview of the assumed architecture and capacity in selected papers

Architecture	
Parallel	Hawkins (1969); Koriatic and Norman (1989a, 1989b); Proctor et al. (1991); Ratcliff and Hacker (1981) and many more.
Serial	Bamber (1969); Krueger (1978); Nickerson (1965)
Coactive	Miller (1978, 1982)
Capacity	
Unlimited	Assumed by almost everyone.
Limited	Decker (1974); Hawkins and Shigley (1972); Link and Tindall (1971)
Super-capacity	Miller (1978, 1982)

Although the SFT analyses are generally performed at the individual level, we still wanted a representative sample. Moreover, this sample size is the usual number of participants recruited in our laboratory for *Same-Different* studies, as it yields a statistical power to detect the fast-same effect (estimated to be a Cohen's d of about 0.4) well above 80% (Goulet & Cousineau, 2019). Therefore, we stopped data collection at twenty participants.

That said, since our main hypotheses are tested using SFT, the true statistical power of our study resides in the number of trials in each condition for every participant. We opted for 256 trials per condition and for the two responses, or 4096 trials in total, which fits well within four sessions. Therefore, we calculated, at an individual level, the statistical power of 256 replications to detect small effects. For z tests (used for MIC and capacity), it represents a power of 89%, whereas for the Kolmogorov-Smirnov tests (used for SIC), it represents a power well above 95% (Boyerinas, 2016).

Procedure

The stimuli are displayed on a CRT monitor (1024×768 pixels) with a refresh rate of 85 Hz situated at approximately 50 cm of the participant. A trial starts with a fixation point located at the centre of the screen, for a duration of 506 ms. Following the fixation point, the first array of letters – S_1 – (horizontal visual angle of about 5.2°) is presented slightly above the fixation point (visual angle of about 4.0°) for 400 ms, then disappears. The inter-stimulus interval lasts 400 ms, during which a blank screen is presented to the participant. Finally, the second array of letters – S_2 – appears slightly below the centre of the screen (visual angle of about –4.0°) for 5000 ms, or until the participant provides a response.

In all the trials, S_1 is clearly visible and composed of two letters. The experimental manipulation is only applied to S_2 . The manipulation consists in altering the clarity of the leftmost letter (attribute #1) and/or the rightmost letter (attribute #2). In conditions where only one letter is presented in S_2 , the attribute presented conserve its physical position in the array. In other words, the letter is either displayed on the leftmost or on the rightmost location of the array, and not in the centre.

The task of the participant is to compare the letter(s) displayed in S_2 with the letter(s) displayed in S_1 at their corresponding positions. Therefore, they can perform a maximum of two comparisons: the leftmost letter presented at S_1 with the leftmost letter presented at S_2 , and/or the rightmost letter presented at S_1 with the rightmost letter presented at S_2 . The participant must not make cross-position comparisons

(i.e., the leftmost letter of S_1 and the rightmost letter of S_2 , and vice-versa).

Stimuli

The stimuli are arrays of one or two letters composed of a random combination of uppercase consonants sampled from a set of twelve (B, C, D, F, J, K, L, N, S, T, V, and Z) taken from Bamber (1969). They are presented in white on a black background using an arial font. In a single array, no letter is repeated. The participant's task is to indicate if all the attributes (letters) match or if at least one of the attribute mismatches. In the former case, the correct answer is *Same*, and in the latter case, the correct answer is *Different*. A matching attribute signifies that the same letter at the same position is present in both pairs. A mismatching attribute signifies that a letter differs between the two pairs at a certain location.

In some conditions, one or two letters are slightly blurred using the *Blur* function in Mathematica (version 11.2.0.0) with a radial blur of 3 pixels. The participants are asked to ignore this blur. The complete list of stimuli is available at the following link: <https://osf.io/cwm26>.

Design

In this experiment, four independent variables are manipulated: i) the clarity of the leftmost letter (2 levels: clear or blurry); ii) the clarity of the rightmost letter (2 levels: clear or blurry); iii) the number of displayed attributes at S_2 (2 levels: one or two) and iv) the identity of the stimulus (2 levels: *Same* or *Different*). For trials with a single letter, the letter was on the right or on the left an equal number of times. In total, sixteen conditions are presented an equal number of times to the participants (all possible combination of independent variables). A summary of the conditions is illustrated in Fig. 1 for a hypothetical trial in which S_1 is composed of the letters “JC”. The dependent variable is the RT; it is measured with a precision of ± 1 ms using E-Prime 2.0 (Psychology Software Tools, 2019).

To ensure adequate estimations of the RT distributions in each condition, participants completed a total of 4096 trials, 256 trials per condition. Because this number represents nearly four hours of testing per participant, the experimental task is divided in four sessions of 1024 trials each. A single session contained 64 trials of each condition. Within a single session, the conditions are randomized. Consequently, on any given trial, the participant could not predict the condition.

Results

All the analyses reported in this section were part of our preregistered analysis plan. We present the results of these

Fig. 1 Experimental design of the current study. In this example, S_1 (not shown) is composed of the letters “J C”. Each box represents a valid S_2 for all 16 possible conditions. On the left plot, the two letters are matching, whereas on the right plot, the two letters are mismatching. The four top-right conditions of the left plot will be used

to assess the architecture of the system responsible to make *Same* judgments, whereas those conditions in the right plot will be used to assess the architecture with regard to *Different* judgments. The other conditions will be useful to assess the capacity coefficient of the system

analyses in four sections. In the first section, we discuss the outlier removals and data cleaning. In the second section, we assess the effectiveness of our manipulations. Precisely, we compare mean RTs for *Same* and *Different* trials across participants, and compare distributions of RTs in the HH, HL, LH and LL conditions. In the third section, we address the question of cognitive architecture and report the mean interaction contrast and the survival interaction contrast for the group data and for individual participants. Finally, in the fourth section, we address the question of processing capacity.

Outlier removal and data aggregation

As established prior to data collection, we removed any trial that timed out (no response after 5000 ms), that were too slow (above 4000 ms) and that were too fast (below 100 ms), as it is unlikely that participants were doing the task as requested for these trials. In total, 172 trials were removed out of 81,920, corresponding of a removal rate of 0.21% of the total trials.

Following our preregistered exclusion criteria, we excluded the data of one participant (#12) from the group analyses because their overall accuracy was three standard deviations below the mean of all participants (z score of -3.39). However, the data of this participant was still analysed at an individual level.

For group analyses, mean RTs represent the mean across all participants. The “average distribution” of RTs across participants was obtained using the technique described in Cousineau, Thivierge, Harding, and Lacouture (2016). This technique consists in aggregating 1 ms bins by computing the geometric mean across participants for every bin after

removing the estimated base response time of individual participants (T_0) and adding the average T_0 to the computed averaged quantiles (also see Thomas & Ross, 1980).

Fast-same effect and manipulation effectiveness

Before testing our main hypotheses, we verify that 1) the fast-same effect is observed and 2) our manipulations are effective. For the former, we looked at mean RTs in every condition (HH, HL, LH, LL, HX, LX, XH and XL) and for each response (*Same* and *Different*). We originally planned to conduct a paired-sample t -test between the mean RTs in the *Same* trials and the mean RTs in the *Different* trials. However, after plotting the mean RTs (see Fig. 2), we decided to change our analysis plan to focus on RT differences between *Same* and *Different* trials by separating conditions in which two letters were presented at S_2 (HH, HL, LH and LL) and conditions in which one letter was presented at S_2 (HX, LX, XH and XL).

In trials for which two letters were presented at S_2 , the fast-same effect is about 32 ms, 95% confidence interval, CI, of [15,50], $t(18) = 3.97$, $p < .001$, $BF = 24.38$, $d = 0.91$.¹ This corresponds to what is typically observed in *Same-Different* tasks. However, we do not observe the same trend for trials in which only one letter is presented at S_2 . To investigate the RTs, we used a 2×4 repeated-measures analysis of variance

¹ For the Bayes factor, our prior is a Cauchy distribution with a location parameter = 0.4 and a scale parameter = $(\sqrt{2}/2)$ following the recommendation of Wagenmakers et al. (2018).

Fig. 2 Mean response times (in ms) as a function of the experimental condition and the response (*Same* or *Different*) for correct trials. For the conditions displayed in the left plot, two letters are presented at S_2 ,

whereas for the conditions displayed in the right plot, one letter is presented at S_2 . Error bars are difference- and correlation-adjusted 95% confidence intervals of the mean

(ANOVA) on the factors *Response* (*Same* or *Different*) and *Condition* (HX, LX, XH and XL). We found that these two factors interacted ($F(3,54) = 4.214$, $p = .009$, $BF = 33.59$, $\eta_p^2 = .190$).² Indeed, there seems to be two elements that affect RT. First, when the letter is blurry, the mean RT increases in both *Same* and *Different* conditions. This trend was expected and shows that the blurring manipulation was effective. Second, when only the leftmost letter was presented, participants were faster to respond *Same* compared to when only the rightmost letter was presented. This effect was not observed when participants were responding *Different*. A consequence of this is that the fast-same effect is reduced in trials in which only one letter is presented at S_2 and even reversed when it is the leftmost letter that is absent.

Typically, when a single letter is presented in both S_1 and S_2 , the fast-same effect is still observed. In our experiment, when only one letter was presented at S_2 , there were two letters presented at S_1 . Therefore, in those conditions in our study, S_2 does not perfectly match S_1 (there is one letter missing). This suggests that even though participants only need one matching letter to respond *Same*, they still expect to encode two letters, and set their decision threshold accordingly. If such is the case, participants would lack activation in these trials, resulting in slower RTs. Yet, this does not explain the differences for HX/LX vs. XH/XL trials. It might be due to a serial treatment of the information, which we assess in our next planned analyses. The question remains why such discrepancy is not observed in *Different* trials. We will discuss this strange result later in the Discussion.

Another potential explanation for the reduced or reversed fast-same effect in single-letter trials is response competition. In these conditions, the absence of a letter can be seen as evidence against the *Same* response. After all, S_2 does not perfectly match S_1 . In summary, even though we did not anticipate this trend in the data, we still wanted to report our post hoc exploration for sake of transparency.

Before continuing our main analyses, we also test the effectiveness of our manipulations. To do so, we used Kolmogorov-Smirnov tests for distribution ordering (Houpt et al., 2014). Such tests ensure that the distribution of the HH condition is faster than the HL and the LH conditions, and that the distribution of the LL condition is slower than the HL and the LH conditions. We conducted these tests for *Same* and *Different* trials separately. Unfortunately, in both *Same* and *Different* trials, the Kolmogorov-Smirnov tests show that the group distributions of RTs are similar between the HH and the HL / LH conditions, and between the LL and the HL / LH conditions. In other words, our manipulations on the clarity of the letters did not slowed down participants as much as anticipated.

Because the manipulation was not as effective as anticipated, we cannot draw strong theoretical conclusions about the cognitive architecture underlying *Same-Different* judgments. For sake of transparency, and because we planned to conduct these analyses, we nevertheless report the MIC and SIC(t) of the group data, but we will put more emphasis on individual participant analyses, particularly on participants for which the manipulation was effective.

Cognitive architecture

The data used in the group analysis are the mean RTs and average distributions of 19 participants in each condition. Using these measures, we conducted two SFT analyses: 1) the mean interaction contrast and 2) the survival interaction contrast. These two analyses are used to diagnose the cognitive architecture and stopping rule. Each analysis is conducted separately for *Same* and *Different* trials.

The MIC is used to estimate whether the cognitive architecture is serial, parallel or coactive. It corresponds to the difference between the two extreme conditions (HH and LL) and the two middle conditions (HL and LH). The means are illustrated in Fig. 3. Using a 2×2 analysis of variance (ANOVA), we can test whether this interaction differs or not from zero, which if it does, would signify that the architecture

² Because this analysis was not planned, we used a null prior.

is either parallel or coactive. For *Same* trials, the MIC = -0.70 ms, suggesting that the architecture is likely serial, $F(1, 72) < 0.01$, $p = .99$. For *Different* trials, the MIC = -5.82 ms, suggesting again that the architecture is likely serial, $F(1, 72) = 0.01$, $p = .91$.

The SIC is used like the MIC to identify which architecture characterizes the cognitive process. It further provides information about the stopping rule of the decision process, that is, either self-termining or exhaustive. The SIC curves are computed the same way as the MIC but using the distribution of RTs instead of only the mean RTs. Two Kolmogorov-Smirnov tests are used to determine whether the maximum and the minimum values of the SIC are different from zero. The group SIC curve is displayed in Fig. 4 (in black), along with the SIC curves of individual participants (in grey or in colour). Because the average distributions are calculated using the geometric mean (Cousineau et al., 2016), the 95% confidence boundaries (in dark grey) are based on the standard errors of the geometric mean (Harding, Tremblay, & Cousineau, 2014).

For *Same* trials, both the maximum and the minimum values of the SIC are not different from zero ($D^+ = 0.03$, $p = .912$; $D^- = -0.01$, $p = .987$). This signifies that the architecture is likely serial and that the stopping rule is likely self-terminating. In other words, participants process letters in sequence and stop their processing as soon as one letter is identified as matching. Similar results observed for *Different* trials ($D^+ = 0.02$, $p = .971$; $D^- = -0.02$, $p = .928$) suggests that processing stops as soon as one letter is identified as mismatching.

Because the blurring manipulation was not as effective as anticipated, we must consider the possibility that it precluded the detection of a parallel or coactive architecture. That said, for some participants, the manipulation was effective. For instance, in the *Same* condition, Kolmogorov-Smirnov tests show that blurring the letter slowed down participants 5, 7, 8, 9 and 18. Participant 8 exhibited a parallel self-terminating architecture in this condition. The SIC(t) curve of this participant is highlighted with the blue colour, in the top panel of

Fig. 4. The other four participants exhibited a serial self-terminating architecture. We also highlight the results of another participant (15), for who even though the MIC suggests a serial architecture, the Kolmogorov-Smirnov tests of their SIC(t) curve show that this participant might have exhibited a parallel exhaustive treatment of the stimuli. This participant is highlighted in the top panel of Fig. 4 with a light red colour.

In the *Different* condition, the blurring manipulation did not slow down any participant. That said, we were still able to detect that participant 18 used a parallel self-terminating architecture. Also, like was the case for participant 15 in the *Same* condition, participant 13 in the *Different* condition, despite a MIC suggesting a serial architecture, exhibited a parallel exhaustive treatment when looking at their SIC(t) curve. This participant is highlighted with the light red colour in the bottom panel of Fig. 4.

Table 2 provides a summary of individual SFT tests for every participant. Again, since the manipulation was not as effective as anticipated, we cannot draw strong conclusions regarding the cognitive architecture underlying *Same-Different* judgments. That being said, we can focus on participants for which the manipulation was effective to gather at least some direction. Despite their differences, the aforementioned participants do not seem to have faster RTs or better accuracy compared to the other participants. This shows that not all participants approach the task the same way, but that the most predominant architecture was serial, that is processing one letter at a time, for both the *Same* and the *Different* trials. At the light of these results, we can argue that the cognitive architecture does not seem to explain why *Same* trials are faster than *Different* trials.

Capacity coefficient

The capacity coefficient is used to estimate whether the efficiency of the cognitive system is limited, unlimited or super capacity. It is computed by comparing the distribution of RT in

Fig. 3 Mean response times (in ms) as a function of the clarity of the leftmost letter and the clarity of the rightmost letter, for *Same* trials (left plot) and *Different* trials (right plot) when both letters were presented.

These plots illustrate the Mean Interaction Contrasts (MIC). Error bars are 95% confidence intervals of the mean

the HH condition to an estimated distribution for an unlimited capacity using the HX and the XH conditions. Using a z test, we can assess the observed effect of increased workload compared to this predicted null effect (unlimited capacity). The group results are summarized in Fig. 4 (in black) along with individual capacity coefficient curves (in grey and colour). The dashed line represents theoretical unlimited capacity. The 95% confidence intervals (in dark grey) are calculated again using the standard error of the geometric mean (Harding et al., 2014).

For *Same* trials, although the capacity tends to be limited, the statistical test shows that the overall capacity is unlimited ($z = -1.37$, $p = .172$). Looking at Fig. 5 to understand this discrepancy, we see that the capacity coefficient does not

reach an asymptote until about 500 ms; before this time, it seems strongly super-capacity. This suggests that participants might benefit from redundancy at first but are quickly hindered by the presence of additional letters. In contrast, for *Different* trials, the capacity is immediately limited, as supported by the statistical test ($z = -3.86$, $p < .001$). When the letters are different, participants are systematically hindered by the increase in workload.

It is typical to observe large oscillations in the capacity coefficient in the first few hundred milliseconds. However, looking at Fig. 5, it is clear that the differences between the *Same* capacity and the *Different* capacity curves are not caused by a statistical fluke. For instance, the group capacity coefficient curve for *Same* trials intersects with the unlimited

Fig. 4 Survival Interaction Constrasts (SIC(t)) for *Same* (top) and *Different* (bottom) trials. The group average is represented by the black line, accompanied by the 95% confidence intervals of the geometric mean (in dark grey). Individual participants are depicted in light grey (serial

self-terminating), in light red (participant for which the SIC(t) suggest parallel exhaustive treatment, but for which the MIC suggests a serial treatment) and blue (parallel self-terminating)

capacity reference line ($C(t) = 1$) at 457 ms, whereas the group capacity coefficient curve for *Different* trials is always below the unlimited capacity reference line. This discrepancy in capacity coefficients between *Same* and *Different* trials could potentially explain why *Same* responses are faster than *Different* responses. Looking at individual participants, whereas they all showed a limited capacity in *Different* trials, some participants had unlimited or super-capacity in the *Same* trials (listed in Table 2).

Let us return to the unexpected result in trials with only one letter presented at S_2 . Recall that in *Same* trials, participants were faster to respond when the leftmost letter was presented compared to when the rightmost letter was presented, an effect not observed in *Different* trials. We argued earlier that there might be more response competition in these trials, which inhibits the *Same* response. A consequence of this response competition is that it would decrease the capacity advantage that benefit *Same* responses. This would explain why the

Table 2 Summary of individual participant analyses

Subject	Condition	MIC	SIC(t)+	SIC(t)-	Capacity	Summary
1	Same	2.87, $p = .918$	0.03, $p = .871$	0.10, $p = .276$	-3.06, $p = .002$	Serial Self-Terminating; Limited Capacity
	Different	7.09, $p = .865$	0.06, $p = .600$	0.13, $p = .138$	-7.98, $p < .001$	Serial Self-Terminating; Limited Capacity
2	Same	7.54, $p = .593$	0.05, $p = .771$	0.11, $p = .215$	0.30, $p = .767$	Serial Self-Terminating; Unlimited Capacity
	Different	-9.14, $p = .496$	0.02, $p = .968$	0.09, $p = .367$	-4.61, $p < .001$	Serial Self-Terminating; Limited Capacity
3	Same	23.46, $p = .168$	0.10, $p = .274$	0.06, $p = .597$	-2.71, $p = .007$	Serial Self-Terminating; Limited Capacity
	Different	-15.79, $p = .343$	0.04, $p = .792$	0.07, $p = .495$	-7.09, $p < .001$	Serial Self-Terminating; Limited Capacity
4	Same	-3.22, $p = .846$	0.04, $p = .789$	0.07, $p = .524$	-2.67, $p = .008$	Serial Self-Terminating; Limited Capacity
	Different	-7.04, $p = .699$	.037, $p = .849$	0.07, $p = .575$	-8.20, $p < .001$	Serial Self-Terminating; Limited Capacity
5	Same	15.77, $p = .373$	0.06, $p = .624$	0.06, $p = .683$	0.21, $p = .836$	Serial Self-Terminating; Unlimited Capacity
	Different	6.85, $p = .709$	0.06, $p = .656$	0.03, $p = .903$	-8.50, $p < .001$	Serial Self-Terminating; Limited Capacity
6	Same	-14.68, $p = .594$	0.02, $p = .968$	0.07, $p = .545$	-1.85, $p = .065$	Serial Self-Terminating; Unlimited Capacity
	Different	25.74, $p = .210$	0.13, $p = .152$	0.01, $p = .152$	-7.28, $p < .001$	Serial Self-Terminating; Limited Capacity
7	Same	-0.66, $p = .957$	0.06, $p = .618$	0.08, $p = .441$	3.30, $p < .001$	Serial Self-Terminating; Super Capacity
	Different	-38.51, $p = .101$	0.02, $p = .952$	0.14, $p = .078$	-5.25, $p < .001$	Serial Self-Terminating; Limited Capacity
8	Same	24.59, $p = .041$	0.16, $p = .035$	0.04, $p = .843$	-1.26, $p = .208$	Parallel Self-Terminating; Unlimited Capacity
	Different	2.30, $p = .821$	0.06, $p = .682$	0.08, $p = .428$	-4.02, $p < .001$	Serial Self-Terminating; Limited Capacity
9	Same	-3.81, $p = .853$	0.11, $p = .204$	0.04, $p = .822$	-4.46, $p < .001$	Serial Self-Terminating; Limited Capacity
	Different	-23.64, $p = .435$	0.01, $p = .979$	0.10, $p = .302$	-5.35, $p < .001$	Serial Self-Terminating; Limited Capacity
10	Same	3.37, $p = .733$	0.11, $p = .196$	0.05, $p = .723$	-3.41, $p < .001$	Serial Self-Terminating; Limited Capacity
	Different	-10.79, $p = .333$	0.03, $p = .877$	0.07, $p = .526$	-4.45, $p < .001$	Serial Self-Terminating; Limited Capacity
11	Same	-94.77, $p = .201$	0.04, $p = .865$	0.09, $p = .389$	-5.09, $p < .001$	Serial Self-Terminating; Limited Capacity
	Different	-20.14, $p = .769$	0.12, $p = .162$	0.06, $p = .662$	-5.81, $p < .001$	Serial Self-Terminating; Limited Capacity
12	Same	-1.79, $p = .849$	0.07, $p = .552$	0.12, $p = .211$	-1.69, $p = .090$	Serial Self-Terminating; Unlimited Capacity
	Different	2.62, $p = .831$	0.12, $p = .239$	0.04, $p = .875$	-8.18, $p < .001$	Serial Self-Terminating; Limited Capacity
13	Same	-14.20, $p = .419$	0.02, $p = .948$	0.08, $p = .263$	-5.11, $p < .001$	Serial Self-Terminating; Limited Capacity
	Different	-16.59, $p = .408$	0.03, $p = .882$	0.16, $p = .048$	-8.39, $p < .001$	Serial Self-Terminating; Limited Capacity
14	Same	-0.10, $p = .994$	0.07, $p = .520$	0.06, $p = .668$	-0.93, $p = .351$	Serial Self-Terminating; Unlimited Capacity
	Different	5.04, $p = .735$	0.10, $p = .308$	0.04, $p = .818$	-5.83, $p < .001$	Serial Self-Terminating; Limited Capacity
15	Same	-23.38, $p = .357$	0.02, $p = .929$	0.17, $p = .032$	-3.24, $p = .001$	Serial Self-Terminating; Limited Capacity
	Different	-3.75, $p = .861$	0.07, $p = .507$	0.07, $p = .498$	-6.51, $p < .001$	Serial Self-Terminating; Limited Capacity
16	Same	21.93, $p = .554$	0.06, $p = .678$	0.10, $p = .228$	-5.71, $p < .001$	Serial Self-Terminating; Limited Capacity
	Different	-8.67, $p = .826$	0.05, $p = .767$	0.04, $p = .801$	-7.45, $p < .001$	Serial Self-Terminating; Limited Capacity
17	Same	9.42, $p = .506$	0.11, $p = .258$	0.11, $p = .244$	-4.26, $p < .001$	Serial Self-Terminating; Limited Capacity
	Different	-2.99, $p = .851$	0.04, $p = .834$	0.12, $p = .150$	-6.51, $p < .001$	Serial Self-Terminating; Limited Capacity
18	Same	14.43, $p = .153$	0.15, $p = .070$	0.04, $p = .815$	3.09, $p = .002$	Serial Self-Terminating; Super Capacity
	Different	29.92, $p = .005$	0.15, $p = .066$	0.01, $p = .991$	-9.08, $p = .001$	Parallel Self-Terminating; Limited Capacity
19	Same	6.40, $p = .747$	0.07, $p = .580$	0.04, $p = .779$	3.31, $p = .001$	Serial Self-Terminating; Limited Capacity
	Different	-9.03, $p = .559$	0.03, $p = .877$	0.08, $p = .490$	-5.80, $p < .001$	Serial Self-Terminating; Limited Capacity
20	Same	11.77, $p = .393$	0.13, $p = .121$	0.02, $p = .946$	-5.98, $p < .001$	Serial Self-Terminating; Limited Capacity
	Different	-21.42, $p = .125$	0.02, $p = .969$	0.12, $p = .168$	-5.02, $p < .001$	Serial Self-Terminating; Limited Capacity

The column MIC reports the mean interaction contrast and the p value of the interaction. The column SIC(t)+ reports the Kolmogorov-Smirnov D statistic and the p value of the test for the positive portion of the curve and the column SIC(t)- for the negative portion of the curve. The column Capacity reports the capacity coefficient and the p value of the Kolmogorov-Smirnov test

capacity coefficient decreases to reach an asymptote at limited capacity as it does in the *Different* trials.

Discussion

The two main objectives of this study were to formally assess the cognitive architecture and processing capacity of the system underlying *Same-Different* judgments. These objectives stem from two roots. First, one result of the *Same-Different* task that has been replicated many times is the fast-same effect, whereby participants respond faster in the *Same* condition compared to the

Different condition. This discrepancy might be explained by different cognitive architectures for the systems underlying *Same* and *Different* judgments. For example, Bamber (1969) proposed that *Same* responses are faster because the underlying system works in parallel, whereas the underlying system of *Different* responses works in serial. The fast-same effect might also be caused by the capacity of the systems, that is how efficiently it can process the information as a function of the workload (the number of information that needs to be treated). Expanding on Bamber (1969), Decker (1974) argued that not only *Different* trials were processed serially, but that they were also subject to a limited capacity. As

Fig. 5 Survival Interaction Constrasts (SIC(t)) for *Same* (top) and *Different* (bottom) trials. The group average is represented by the black line, accompanied by the 95% confidence intervals of the geometric mean (in dark grey). Note that the confidence intervals are close to the group

curve and might not be obvious at first glance. Individual participants are depicted in light grey (limited capacity), in red (unlimited capacity) and blue (super-capacity)

discussed in the introduction, researchers assumed different architectures and capacity when explaining the fast-same effect (also see Table 1). This leads to the second question: Which theory assumed architecture and capacity correctly?

The results of the current study are – unfortunately – not conclusive enough to make any strong claim regarding cognitive architecture, because the blurring manipulation was not as effective as anticipated. At best, the results suggest that in both *Same* and *Different* trials, participants processed the letters serially, but that some participants processed the letters in parallel. The serial architecture was originally assumed by many researchers (i.e., Krueger, 1978; Nickerson, 1965). Bamber (1969) and Decker (1974) were also arguing for a serial treatment, but only for *Different* trials (they argued that participants processed *Same* trials in parallel, or *holistically*). Hawkins (1969) highlighted that there was no need for a serial treatment, and that a parallel model could also account for the fast-same effect. One conclusion that we can draw from the results of this study is that the fast-same effect is not dependant on the underlying cognitive architecture: Different participants had different architecture without apparent effect on the presence of the fast-same effect.

Another critical assumption made by most researchers is that the workload does not affect the processing efficiency of the system underlying *Same-Different* judgments. In our study, we observed that most participants had an overall limited capacity in *Different* trial. Only a few theories accounted for this hindrance in capacity for the *Different* trials (Decker, 1974; Hawkins & Shigley, 1972; Link & Tindall, 1971). That said, these researchers also argued that there was some form of parallel processing in the *Same* condition. As for *Same* trials, i) the capacity coefficient asymptote is reached less rapidly, and ii) there exists greater individual differences. The results show that in the first 500 ms, participants are more efficient at processing *Same* information compared to *Different* information. However, possibly due to response competition, participants capacity recedes towards limited capacity. This initial, short-lasting, but strong boost in processing capacity could explain why *Same* responses are faster than *Different* responses. This is novel result, as no theory ever explicitly attributed the fast-same effect solely to processing capacity.

Capacity and the fast-same effect

Miller's model (1978, 1982) stands out as an outlier in the *Same-Different* task models, proposing that the system underlying the task might work in coactivity and in super-capacity. Whereas the current study does not support this theory, we observe an interesting trend in the capacity coefficients between 300 and 500 ms, which was seen in Fig. 5. Indeed, for *Different* trials, the capacity coefficient is fairly flat and reaches an asymptote at approximately 400 ms). For *Same* trials however, we see that the capacity coefficient is initially super-capacity, then decreasing between 300 and 500 ms, after

which it reaches its asymptote. This signifies that between 300 and 500 ms, the processing capacity is larger in *Same* trials than in *Different* trials. To our knowledge, this *time-limited capacity enhancement* in *Same* trial was never proposed as a potential explanation for the fast-same effect. This is probably because processing capacity was often ignored in models of the *Same-Different* task. That said, we can draw some parallels with Farell (1985)'s model, which highlights the role of attention in the fast-same effect.

In neuropsychological studies, one event-related potential that occurs at around 300 ms after the presentation of a stimulus is the P300. This event-related potential has been associated with workload in short-term memory (Picton, 1992). Typically, a large amplitude of the P300 is associated with a more important workload (i.e., in n-back tasks, Scharinger, Soutschek, Schubert, & Gerjets, 2017). It could also be associated with participants paying more attention to an unexpected stimulus (Picton, 1992). This resonates with Farell (1985)'s model of the *Same-Different* task. Farell proposed that a single process is underlying the task, but that it is modulated by attention (in the sense that *Different* trials require more attention than *Same* trials because participants are expecting matching stimuli). Perhaps this is mirrored by the lack of processing capacity in the early stages of the processing (the first 500 ms) in *Different* trials, as observed in this study.

It could also explain the unexpected result obtained in trials in which only one letter was presented at S_2 (faster mean RTs when the leftmost letter was presented for *Same* but not for *Different* trials. If participants rely on pre-attentive processing for *Same* trials, they might resort to their default serial scanning. On *Different* trials however, participants already spend attentional resources to process the stimulus and might be better at directing their processing resources at a specific area on the screen.

The potential role of the P300 in the *Same-Different* task remains unclear. One could expect that a larger amplitude of this event-related potential would be associated with more processing capacity. However, it could also be associated with a need for additional attentional resources, which would consequently reduce processing capacity. Indeed, some researchers showed that stimulus treatment and attention are likely in competition for the same resources (Swan & Wyble, 2014; Wyble, Potter, Bowman, & Nieuwenstein, 2011). If *Different* responses require more attention than *Same* responses, as suggested by Farell, this could explain why we observe that *Same* responses benefits, initially, from more processing resources, therefore, from more processing capacity.

Limitations of the current study

One of the main limitations of the study is that the manipulation (i.e., blurring the letters), was not as effective as anticipated. It is difficult to interpret why this occurred. In principle,

participants should be slower to encode/process blurry information compared to clear information. This was not reflected in the Kolmogorov-Smirnov tests conducted to test the efficiency of this manipulation. Perhaps a future replication study could be conducted with the letters being blurred even more. That said, we must consider the possibility that increasing the blurriness of the letters too much might render them undetectable from one another, which would result in massive error rates.

Another limitation is the fact that the number of conditions could be considered rather low from *Same-Different* standards. Indeed, it is not rare to see researchers vary the number of elements (in our case letters) from one to four and the number of mismatching elements from zero to four. For example, Bamber (1969) used fourteen conditions in total (including intermediate conditions such as three letters, one mismatching letter), whereas we used – excluding the conditions in which blurred letters were used – four conditions (one letter, one match or one mismatch; two letters, two matches or two mismatches). We only included these conditions because in addition to our other manipulations, this represented four sessions of one hour for every participant. However, we strongly encourage researchers to include intermediate conditions such as two letters, one mismatching letter (and one matching letter) in future designs.

Final remarks and future directions

Research on the *Same-Different* task blossomed in 1960s and the 1970s, but slowed down in the 1980s, probably due to the plethora of proposed models and the lack of consensus. We identified two unsupported assumptions that present a point of discord between models: cognitive architecture and processing capacity. In order to be as objective as possible in answering this question, we preregistered an experimental protocol that aimed to directly assess those two research questions. We found that the cognitive architecture does not seem to influence the fast-same effect.

We also found that *Different* trials were characterized by limited processing capacity, whereas most models of the *Same-Different* task assumed (by default) that the processing capacity was unlimited (the few exceptions being Decker, 1974; Hawkins & Shigley, 1972 and Link & Tindall, 1971). In contrast, *Same* trials were characterized by a more ambiguous processing capacity, as illustrated in Fig. 5. Overall, the system was working somewhere between unlimited and limited capacity. However, between 300 and 500 ms, we found that the capacity coefficient in *Same* trials is super-capacity, after which it reaches an asymptote.

Future work should focus on this discrepancy in processing capacity between *Same* and *Different* trials. A good approach would be to use electroencephalogram (EEG) data and explore event-related potentials around 300–500 ms (such as the P300) in a *Same-Different* design. Specifically, it would

be pertinent to see if the P300 amplitude varies between *Same* and *Different* trials.

Open practices statement The material, raw data (before outlier removal) and analysis scripts are available on the Open Science Framework (OSF) page for this project: <https://osf.io/cwm26>.

Funding This research was funded by Denis Cousineau's research grant from Natural Sciences and Engineering Research Council of Canada (RGPIN/2016–03906).

Mean Interaction Contrast (MIC)

Using the double-factorial design, mean RTs can be computed for the HH, HL, LH and LL conditions. Using these four means, the Mean Interaction Contrast (MIC) can be calculated using this formula:

$$MIC = (\overline{RT}_{HH} + \overline{RT}_{LL}) - (\overline{RT}_{HL} + \overline{RT}_{LH}) \quad (1)$$

The MIC can provide insightful information about the architecture of the cognitive system. If the system is working in serial, the slowdown in processing caused by the L manipulation on isolated attributes (HL and LH conditions) should stack in the LL condition. Therefore, the MIC should be equal or close to 0. If the MIC is lower than 0, it suggests that the architecture is parallel, and the stopping rule is exhaustive. Indeed, the probability of the two channels completing their processing after t ms is decreased when an attribute is in the L condition. The probability of one channel being very slow increases when the two dimensions are in the L condition. Conversely, the probability of either of the two channels completing their processing after t ms is increased when an attribute is in the H condition. The probability of a channel being very fast increases when the two attributes are in the H condition. Therefore, when the architecture is parallel, and the stopping rule is self-terminating, the MIC is greater than 0. When the architecture is coactive, the MIC is also greater than 0, because an increase in the channel processing rates signifies that the common threshold will be reached faster.

Despite being a useful tool, the MIC is limited to the mean RT and cannot distinguish between stopping rules for serial architecture, or between a parallel self-terminating and a coactive system (Harding et al., 2016). To alleviate these limitations, the SFT uses the whole distribution of RTs.

Survival Interaction Contrast (SIC)

The probability density function (PDF) corresponds to the density of observing a response at precisely t ms. Another way of estimating the distribution of RT is to compute the

probability of observing a response before t ms, that is the cumulative density function (CDF). Alternatively, one could compute the probability of no response being observed before t ms, that is $1 - \text{CDF}$, called the survivor function (SF). The SF is a useful tool to illustrate a mental process and can be portrayed as the probability of the cognitive system still being active (or still accumulating information) after t ms.

Analogous to the computation of the MIC, the *Survivor Interaction Contrast* (SIC) can be calculated for every time point of t (in ms). Using the SF of all four conditions (HH, HL, LH and LL), the $\text{SIC}(t)$ can be obtained using this formula:

$$\text{SIC}(t) = (\text{SF}_{\text{HH}}(t) + \text{SF}_{\text{LL}}(t)) - (\text{SF}_{\text{HL}}(t) + \text{SF}_{\text{LH}}(t)) \quad (2)$$

Plotting the $\text{SIC}(t)$ curve provides the researcher with a diagnostic tool to detect the architecture and the stopping rule of a cognitive system (Townsend & Nozawa, 1995). Appendix A Fig. 6 pictures the five distinct $\text{SIC}(t)$ signature curves. A Kolmogorov-Smirnov test can be used to evaluate if the minimum and the maximum are different from zero (Houtp & Burns, 2017; Houtp & Townsend, 2010).

A serial self-terminating architecture is characterized by a flat $\text{SIC}(t)$ curve, where neither the positive nor the negative portion are different from zero. A serial exhaustive architecture is characterized by a negative portion at the beginning of the curve and a positive portion at the end of the curve. A parallel self-terminating architecture is characterized by a negative portion only, whereas a parallel exhaustive architecture

is characterized by a positive portion only. Finally, the coactive architecture show similarity with the serial exhaustive curve, starting with a small negative portion, then with a larger positive portion. The MIC should be used to distinguish between these two architectures.

Although the $\text{SIC}(t)$ signature curves are shown to be a powerful tool to detect architecture and stopping rules, some situations might lead to misdiagnosis. If the decision thresholds of a system are highly variable, $\text{SIC}(t)$ curves might mimic a parallel self-terminating architecture, as shown by Harding, LeBlanc, Goulet, and Cousineau (2017). Misdiagnosis might also arise from noisy data caused by non-equivalent manipulations on the two attributes. Indeed, if the salience of each source of information is inappropriately balanced in the factorial manipulation, one attribute could be overly represented in some conditions and add noise to the $\text{SIC}(t)$ curves (Houtp & Fifić, 2017). As $\text{SIC}(t)$ curves are estimated from a finite number of trials, the estimated SF curves can be sensible to asymmetric manipulation design. Finally, some researches have recently suggested that participants might use mixtures of architecture throughout the experimental session. In other words, some participants might use a parallel strategy, say for 60% of the trials, and a serial strategy for the remaining 40% of the trials (Little, Nosofsky, & Denton, 2011; Moneer, Wang, & Little, 2016). Although $\text{SIC}(t)$ curves can still be used to test the plausibility of mixture architectures, they must be compared with the predictions made by mixture models fitting.

Fig. 6 Survival interaction contrasts ($\text{SIC}(t)$) signature curves for all five architectures and stopping rule combinations. The panel a) corresponds to a system working in serial with a self-terminating stopping rule. The curve resembles a flat line and does not deviate from 0. The panel b) corresponds to a system working in serial with an exhaustive stopping rule. The negative and the positive areas under the curve differ from zero but are equal. The panel c) corresponds to a system working in parallel with a self-terminating stopping rule. Only the positive portion is different

from zero. The panel d) corresponds to a system working in parallel with an exhaustive stopping rule. Only the negative portion is different from zero. Finally, the panel e) corresponds to a system working in coactivity. The curve resembles the serial exhaustive curve, as both the positive and the negative portions are different from zero. However, the area under the curve in the positive portion is higher than the area under the curve in the negative portion

Capacity Coefficient

To answer questions regarding the capacity of the cognitive system, SFT uses conditions where only one attribute is presented to the participants. Essentially, capacity assess whether increasing the workload of the task (increasing the number of active channels or the complexity of the stimulus) affects the processing rates of the channel. SFT measures the capacity coefficient by comparing conditions where one attribute is present to conditions where two attributes are present.

The computation of the capacity coefficient requires the use of cumulative hazard functions (CHF), which correspond to the probability at t ms of the response occurring on the next iteration, given that no response has been given before t ms. Alternatively, it can be described as the probability that a state change is imminent (Chechile, 2011).

The CHF of three conditions must be estimated to calculate the capacity coefficient in self-terminating designs (OR designs): two conditions in which the single dimensions are presented (HX and XH) and the redundant condition (HH) (Altieri, Fifić, Little, & Yang, 2017; Harding et al., 2016; Houpt et al., 2014). To compute the capacity coefficient of an OR design, the following formula must be used:

$$C_{OR} = \frac{CHF_{HH}(t)}{CHF_{HX}(t) + CHF_{XH}(t)} \quad (3)$$

In cases of exhaustive designs (AND designs), where both dimensions must be obligatory assessed before providing a response, the capacity coefficient is computed using reversed hazard functions (K) instead of CHF (Altieri et al., 2017; Harding et al., 2016; Houpt et al., 2014). To compute the capacity coefficient of an AND design, the following formula must be used:

$$C_{AND} = \frac{K_{HX}(t) + K_{XH}(t)}{K_{HH}(t)} \quad (4)$$

For the sake of simplicity, we will further refer to the adequate capacity coefficient – C_{OR} or C_{AND} – as $C(t)$. If the value of $C(t)$ is equal to 1, the system works with full capacity. Adding more attributes does not increase nor decrease the capacity of the channels compared to conditions where only one attribute is shown. If the value of $C(t)$ is lower than 1, the system works with limited capacity. The increase in dimensions hinders the processing rate of the channels compared to conditions where only one dimension is shown. Finally, if the value of $C(t)$ is greater than 1, the system works with super capacity. Herein, more attributes speed up the processing rate of the channels in comparison to conditions where only one attribute is presented. Figure 7 illustrates capacity coefficient signatures of full, limited and super capacity systems.

The capacity coefficient can be statistically tested using a z test on any given value of t (Houpt & Burns, 2017). Although

Fig. 7 Capacity coefficient ($C(t)$) signature curves for all three workload capacity types. Each plot contains a reference line at $C(t) = 1$, corresponding to the system working at full capacity. The panel a) corresponds to a system working at limited capacity. The curve is below the reference line. The panel b) corresponds to a system working

at unlimited capacity. The curve is directly on the reference line except for oscillations for small RTs owing to near-zero counts. The panel c) corresponds to a system working at super capacity. The curve is above the reference line. When the system benefits a lot from additional channels, $C(t)$ will likely have very high values (> 1000)

the test can be repeated for every value of t , it is recommended to limit the number of tests to avoid the increased risk of committing a Type I error. Thus, the capacity coefficient should be tested using a log-rank test, as described in Hout & Townsend (2012).

References

- Altieri, N., Fifić, M., Little, D. R., & Yang, C.-T. (2017). Historical foundations and a tutorial introduction to systems factorial technology. In Daniel R Little, N. Altieri, M. Fifić, & C.-T. Yang (Eds.), *Systems factorial technology: A theory driven methodology for the identification of perceptual and cognitive mechanisms* (pp. 3–26). Academic Press. <https://doi.org/10.1016/B978-0-12-804315-8.00002-1>
- Ashby, F. G., & Townsend, J. T. (1986). Varieties of perceptual independence. *Psychological Review*, 93(2), 154–179. <https://doi.org/10.1037/0033-295X.93.2.154>
- Atkinson, R. C., Holmgren, J. E., & Juola, J. F. (1969). Processing time as influenced by the number of elements in a visual display. *Attention, Perception, & Psychophysics*, 6(6), 321–326. <https://doi.org/10.3758/BF03212784>
- Bamber, D. (1969). Reaction times and error rates for “same” – “different” judgments of multidimensional stimuli. *Perception & Psychophysics*, 6(3), 169–174. <https://doi.org/10.3758/BF03210087>
- Bamber, D., Herder, J., & Tidd, K. (1975). Reaction times in a task analogous to “same” – “different” judgment. *Perception & Psychophysics*, 18(5), 321–327. <https://doi.org/10.3758/BF03211207>
- Bindra, D., Donderi, D. C., & Nishisato, S. (1968). Decision Latencies of same and Different judgments. *Perception & Psychophysics*, 3(2B), 121–130. <https://doi.org/10.3758/BF03212780>
- Bindra, D., Williams, J. A., & Wise, J. S. (1965). Judgments of Sameness and Difference : Experiments on Decision Time. *American Association for the Advancement of Science*, 150(3703), 1625–1627. <https://doi.org/10.1126/science.150.3703.1625>
- Boyerinas, B. M. (2016). Determining the Statistical Power of the Kolmogorov-Smirnov and Anderson-Darling Goodness-of-Fit Tests via Monte Carlo Simulation. In *CNA Occasional Paper* (Issue December).
- Chechile, R. A. (2011). Properties of reverse hazard functions. *Journal of Mathematical Psychology*, 55(3), 203–222. <https://doi.org/10.1016/j.jmp.2011.03.001>
- Cousineau, D., Thivierge, J. P., Harding, B., & Lacouture, Y. (2016). Constructing a group distribution from individual distributions. *Canadian Journal of Experimental Psychology*, 70(3), 253–277. <https://doi.org/10.1037/cep0000069>
- Decker, L. R. (1974). The effect of method of presentation, set, and stimulus dimensions on “same” – “different” reaction times. *Perception & Psychophysics*, 16(2), 271–275. <https://doi.org/10.3758/BF03203941>
- Derks, P. L. (1972). Visual recognition of similarity and identity. *Journal of Experimental Psychology*, 95(1), 237–239. <https://doi.org/10.1037/h0033282>
- Donders, F. C. (1969). On the speed of mental processes. In K. W.G. (Ed.), *Attention and Performance II* (pp. 412–431). North-Holland Publishing Company. [https://doi.org/10.1016/0001-6918\(69\)90065-1](https://doi.org/10.1016/0001-6918(69)90065-1)
- Donkin, C., Little, D. R., & Hout, J. W. (2014). Assessing the Speed - Accuracy Trade-Off Effect on the Capacity of Information Processing. *Journal of Experimental Psychology: Human Perception and Performance*, 40(3), 1183–1202. <https://doi.org/10.1037/a0035947>
- Egeth, H. E. (1966). Parallel versus serial processes in multidimensional stimulus discrimination. *Perception & Psychophysics*, 1(4), 245–252. <https://doi.org/10.3758/BF03207389>
- Eidels, A., Hout, J. W., Altieri, N., Pei, L., & Townsend, J. T. (2011). Nice guys finish fast and bad guys finish last: Facilitatory vs. inhibitory interaction in parallel systems. *Journal of Mathematical Psychology*, 55(2), 176–190. <https://doi.org/10.1016/j.jmp.2010.11.003>
- Eriksen, C. W., O’Hara, W. P., & Eriksen, B. (1982). Response competition effects in same-different judgments. *Perception & Psychophysics*, 32(3), 261–270. <https://doi.org/10.3758/BF03206230>
- Farrell, B. (1977). *Encoding and comparisons in “Same”-“Different” judgments* (Unpublished doctoral thesis). McGill University.
- Farrell, B. (1985). “Same” – “Different” judgments: A review of current controversies in perceptual comparisons. *Psychological Bulletin*, 98(3), 419–456. <https://doi.org/10.1037/0033-2909.98.3.419>
- Godwin, H. J., Walenchok, S. C., Hout, J. W., Hout, M. C., & Goldinger, S. D. (2015). Faster than the speed of rejection: Object identification processes during visual search for multiple targets. *Journal of Experimental Psychology: Human Perception and Performance*, 41(4), 1007–1020. <https://doi.org/10.1037/xhp0000036>
- Goulet, M. A., & Cousineau, D. (2019). The power of replicated measures to increase statistical power. *Advances in Methods and Practices in Psychological Science*, 2(3), 199–213. <https://doi.org/10.1177/2515245919849434>
- Grice, G. R., Canham, L., & Gwynne, J. W. (1984). Absence of a redundant-signals effect in a reaction time task with divided attention. *Perception & Psychophysics*, 36(6), 565–570. <https://doi.org/10.3758/BF03207517>
- Harding, B., Goulet, M. A., Jolin, S., Tremblay, C., Villeneuve, S.-P., & Durand, G. (2016). Systems Factorial Technology Explained to Humans. *The Quantitative Methods for Psychology*, 12(1), 39–56. <https://doi.org/10.20982/tqmp.12.1.p039>
- Harding, B., LeBlanc, V., Goulet, M. A., & Cousineau, D. (2017). Applying systems factorial technology to discrete accumulators with varying thresholds. In D. R. Little, N. Altieri, M. Fifić, & C.-T. Yang (Eds.), *Systems factorial technology: A theory driven methodology for the identification of perceptual and cognitive mechanisms* (1st Edition). Elsevier. <https://doi.org/10.1016/B978-0-12-804315-8.00016-1>
- Harding, B., Tremblay, C., & Cousineau, D. (2014). Standard errors: A review and evaluation of standard error estimators using Monte Carlo simulations. *The Quantitative Methods for Psychology*, 10(2), 107–123. <https://doi.org/10.20982/tqmp.10.2.p107>
- Hawkins, H. L. (1969). Parallel processing in complex visual discrimination. *Perception & Psychophysics*, 5(1), 56–64. <https://doi.org/10.3758/BF03210482>
- Hawkins, H. L., & Shigley, R. H. (1972). Irrelevant information and processing mode in speeded discrimination. *Journal of Experimental Psychology*, 96(2), 389–395. <https://doi.org/10.1037/h0033642>
- Heathcote, A., Brown, S., & Cousineau, D. (2004). QMPE: estimating Lognormal, Wald, and Weibull RT distributions with a parameter-dependent lower bound. *Behavior Research Methods, Instruments, & Computers : A Journal of the Psychonomic Society, Inc.*, 36(2), 277–290. <https://doi.org/10.3758/BF03195574>
- Holmgren, J. E., Juola, J. F., & Atkinson, R. C. (1974). Response latency in visual search with redundancy in the visual display. *Perception and Psychophysics*, 16(1), 123–128. <https://doi.org/10.3758/BF03203264>
- Hout, J. W., Blaha, L. M., McIntire, J. P., Havig, P. R., & Townsend, J. T. (2014). Systems factorial technology with R. *Behavior Research*

- Methods*, 46(2), 307–330. <https://doi.org/10.3758/s13428-013-0377-3>
- Houpt, J. W., & Burns, D. M. (2017). Statistical analyses for systems factorial technology. In Daniel R Little, N. Altieri, M. Fifić, & C.-T. Yang (Eds.), *Systems factorial technology: A theory driven methodology for the identification of perceptual and cognitive mechanisms* (pp. 53–68). Academic Press. <https://doi.org/10.1016/B978-0-12-804315-8.00005-7>
- Houpt, J. W., & Fifić, M. (2017). Adaptive experimental design for systems factorial technology. *Annual Meeting of the Psychonomics Society*.
- Houpt, J. W., & Townsend, J. T. (2010). The statistical properties of the Survivor Interaction Contrast. *Journal of Mathematical Psychology*, 54(5), 446–453. <https://doi.org/10.1016/j.jmp.2010.06.006>
- Howell, P., & Stockdale, J. E. (1975). Memory and display search in binary classification reaction time. *Perception and Psychophysics*, 18(6), 379–388.
- Hylan, J. P. (1903). The distribution of attention - 1. *Psychological Review*, 10(4), 373–403. <https://doi.org/10.1037/h0070820>
- Hyun, J., Woodman, G. F., Vogel, E. K., Hollingworth, A., & Luck, S. J. (2009). The comparison of visual working memory representations with perceptual inputs. *Journal of Experimental Psychology: Human Perception and Performance*, 35(4), 1140–1160. <https://doi.org/10.1037/a0015019>
- Irwin, R. J., Hautus, M. J., & Francis, M. A. (2001). Indices of response bias in the same-different experiment. *Perception & Psychophysics*, 63(6), 1091–1100. <https://doi.org/10.3758/BF03194527>
- Koriat, A., & Norman, J. (1989a). Establishing global and local correspondence between successive stimuli: the holistic nature of backward alignment. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15(3), 480–494. <https://doi.org/10.1037/0278-7393.15.3.480>
- Koriat, A., & Norman, J. (1989b). Why is word recognition impaired by disorientation while the identification of single letters is not? *Journal of Experimental Psychology: Human Perception and Performance*, 15(1), 153–163. <https://doi.org/10.1037/0096-1523.15.1.153>
- Krueger, L. E. (1978). A Theory of Perceptual Matching. *Psychological Review*, 85(4), 278–304. <https://doi.org/10.1037/0033-295X.85.4.278>
- Krueger, L. E. (1983). Probing Proctor's Priming Principle: The Effect of Simultaneous and Sequential Presentation on Same-Different judgments. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 9(3), 511–523. <https://doi.org/10.1037/0278-7393.9.3.511>
- Link, S. W., & Tindall, A. D. (1971). Speed and accuracy in comparative judgments of line length. *Perception and Psychophysics*, 9(3), 284–288. <https://doi.org/10.3758/BF03212649>
- Little, Daniel R, Altieri, N., Fifić, M., & Yang, C.-T. (2017). *Systems Factorial Technology: A Theory Driven Methodology for the Identification of Perceptual and Cognitive Mechanisms* (Daniel R Little, N. Altieri, M. Fifić, & C.-T. Yang (eds.)). Academic Press. <https://doi.org/10.1016/B978-0-12-804315-8.00024-0>
- Little, Daniel R, Eidels, A., Houpt, J. W., & Yang, C.-T. (2017). Set size slope still does not distinguish parallel from serial search. *Behavioral and Brain Sciences*, 40(e145), 32–33. <https://doi.org/10.1017/S0140525X16000157>
- Little, Daniel R, Nosofsky, R. M., & Denton, S. E. (2011). Response-time tests of logical-rule models of categorization. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 37(1), 1–27. <https://doi.org/10.1037/a0021330>
- Luce, D. R. (1986). Memory Scanning, Visual Search, and Same-Different Designs. In *Response Times: Their role in inferring elementary mental organization* (pp. 425–455). Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780195070019.001.0001>
- Miller, J. (1978). Multidimensional same-different judgments: Evidence against independent comparisons of dimensions. *Journal of Experimental Psychology: Human Perception and Performance*, 4(3), 411–422. <https://doi.org/10.1037/0096-1523.4.3.411>
- Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, 14(2), 247–279. [https://doi.org/10.1016/0010-0285\(82\)90010-X](https://doi.org/10.1016/0010-0285(82)90010-X)
- Moneer, S., Wang, T., & Little, D. R. (2016). The processing architectures of whole-object features: A logical-rules approach. *Journal of Experimental Psychology: Human Perception and Performance*, 42(9), 1443–1465. <https://doi.org/10.1037/xhp0000227>
- Mordkoff, J. T., & Yantis, S. (1991). An interactive race model of divided attention. *Journal of Experimental Psychology: Human Perception and Performance*, 17(2), 520–538. <https://doi.org/10.1037/0096-1523.17.2.520>
- Nickerson, R. S. (1965). Response times for “Same” “Different” Judgements. *Perceptual & Motor Skills*, 20, 15–18. <https://doi.org/10.2466/pms.1965.20.1.15>
- Nickerson, R. S. (1967a). Categorization time with categories defined by disjunctions and conjunctions of stimulus attributes. *Journal of Experimental Psychology*, 73(2), 211–219. <https://doi.org/10.1037/h0021270>
- Nickerson, R. S. (1967b). Same-Different response times with multi-attribute stimulus differences. *Perceptual and Motor Skills*, 24, 543–554. <https://doi.org/10.2466/pms.1967.24.2.543>
- Nickerson, R. S. (1973). The use of binary-classification tasks in the study of human information processing: A tutorial survey. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 449–475). Academic Press.
- Nickerson, R. S. (1978). On the time it takes to tell things apart. In J. Requin (Ed.), *Attention and Performance VII* (pp. 77–88). Lawrence Erlbaum Associates.
- Petrov, A. A. (2009). Symmetry-based methodology for decision-rule identification in same-different experiments. *Psychonomic Bulletin & Review*, 16(6), 1011–1025. <https://doi.org/10.3758/PBR.16.6.1011>
- Picton, T. W. (1992). The P300 Wave of the Human Event-Related Potential. *Journal of Clinical Neurophysiology*, 9(4), 456–479. <https://doi.org/10.1097/00004691-199210000-00002>
- Posner, M. I., & Mitchell, R. F. (1967). Chronometric analysis of classification. *Psychological Review*, 74(5), 392–409. <https://doi.org/10.1037/h0024913>
- Proctor, R. W. (1981). A Unified Theory for Matching-Task Phenomena. *Psychological Review*, 88(4), 291–326. <https://doi.org/10.1037/0033-295X.88.4.291>
- Proctor, R. W. (1986). Response bias, criteria settings, and the fast-same phenomenon: A reply to Ratcliff. *Psychological Review*, 93(4), 473–477. <https://doi.org/10.1037/0033-295X.93.4.473>
- Proctor, R. W., Healy, A. F., & Van Zandt, T. (1991). Same-different judgments of multiletter strings: insensitivity to positional bias and spacing. *Perception & Psychophysics*, 49(1), 62–72. <https://doi.org/10.3758/BF03211617>
- Proctor, R. W., & Rao, K. V. (1983a). Reinstating the original principles of Proctor's unified theory for matching-task phenomena: An evaluation of Krueger and Shapiro's reformulation. *Psychological Review*, 90(1), 21–37. <https://doi.org/10.1037/0033-295X.90.1.21>
- Proctor, R. W., & Rao, K. V. (1983b). Evidence that the same-different disparity in letter matching is not attributable to response bias. *Perception & Psychophysics*, 34(1), 72–76. <https://doi.org/10.3758/BF03205898>
- Proctor, R. W., Rao, K. V., & Hurst, P. W. (1984). An examination of response bias in multiletter matching. *Perception & Psychophysics*, 35(5), 464–476. <https://doi.org/10.3758/BF032039231272>
- Psychology Software Tools. (2019). *INFO: E-Prime 2.0 Timing Data [19579]*. <https://support.pstnet.com/hc/en-us/articles/229355247-INFO-E-Prime-2-0-Timing-Data-19579->

- Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, 85(2), 59–108. <https://doi.org/10.1037/0033-295X.85.2.59>
- Ratcliff, R. (1985). Theoretical interpretations of the speed and accuracy of positive and negative responses. *Psychological Review*, 92(2), 212–225. <https://doi.org/10.1037/0033-295X.92.2.212>
- Ratcliff, R., & Hacker, M. J. (1981). Speed and accuracy of same and different responses in perceptual matching. *Perception & Psychophysics*, 30(3), 303–307. <https://doi.org/10.3758/BF03214286>
- Ratcliff, R., McKoon, G., & Verwoerd, M. (1989). A bias interpretation of facilitation in perceptual identification. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15(3), 378–387. <https://doi.org/10.1037/0278-7393.15.3.378>
- Scharinger, C., Soutschek, A., Schubert, T., & Gerjets, P. (2017). Comparison of the working memory load in N-back and working memory span tasks by means of EEG frequency band power and P300 amplitude. *Frontiers in Human Neuroscience*, 11(January), 1–19. <https://doi.org/10.3389/fnhum.2017.00006>
- Sekuler, R. W., & Abrams, M. (1968). Visual Sameness : A choice time analysis of pattern recognition processes. *Journal of Experimental Psychology*, 77(2), 232–238. <https://doi.org/10.1037/h0025741>
- Silverman, W. P., & Goldberg, S. L. (1975). Further confirmation of same vs. different processing differences. *Perception & Psychophysics*, 17(2), 189–193. <https://doi.org/10.3758/BF03203884>
- St. James, J. D., & Eriksen, C. W. (1992). Response competition produces a “fast same effect” in same-different judgments. In J. R. Pomerantz & G. R. Lockhead (Eds.), *Uncertainty and structure as psychological concepts* (pp. 157–168). American Psychological Association. <https://doi.org/10.1037/10101-009>
- Sternberg, S. (1966). High-speed scanning in human memory. *Science*, 153(3736), 652–654.
- Sternberg, S. (1969). The discovery of processing stages: extensions of Donder’s method. In W. G. Koster (Ed.), *Attention and Performance II* (pp. 276–315). North-Holland Publishing Company. [https://doi.org/10.1016/0001-6918\(69\)90055-9](https://doi.org/10.1016/0001-6918(69)90055-9)
- Sternberg, S. (1998). Inferring Mental Operations from Reaction Time Data : How We Compare Objects. In D. Scarborough & S. Sternberg (Eds.), *An invitation to cognitive science* (2nd Editio, Issue 4, pp. 365–454). MIT Press. <https://doi.org/10.1017/CBO9781107415324.004>
- Swan, G., & Wyble, B. (2014). The binding pool: A model of shared neural resources for distinct items in visual working memory. *Attention, Perception, & Psychophysics*, 76(7), 2136–2157. <https://doi.org/10.3758/s13414-014-0633-3>
- Taylor, D. A. (1976). Effect of identity in the multiletter matching task. *Journal of Experimental Psychology: Human Perception and Performance*, 2(3), 417–428. <https://doi.org/10.1037/0096-1523.2.3.417>
- Taylor, D. A. (1977). Time Course of Context Effects. *Journal of Experimental Psychology: General*, 106(4), 404–426. <https://doi.org/10.1037/0096-3445.106.4.404>
- Thomas, E. A. C., & Ross, B. H. (1980). On appropriate procedures for combining probability distributions within the same family. *Journal of Mathematical Psychology*, 21(2), 136–152. [https://doi.org/10.1016/0022-2496\(80\)90003-6](https://doi.org/10.1016/0022-2496(80)90003-6)
- Townsend, J. T. (1972). Some results concerning the identifiability of parallel and serial processes. *British Journal of Mathematical and Statistical Psychology*, 25(2), 168–199. <https://doi.org/10.1111/j.2044-8317.1972.tb00490.x>
- Townsend, J. T., & Ashby, F. G. (1983). *The stochastic modeling of elementary psychological processes*. Cambridge University Press.
- Townsend, J. T., & Eidels, A. (2011). Workload capacity spaces: A unified methodology for response time measures of efficiency as workload is varied. *Psychonomic Bulletin & Review*, 18(4), 659–681. <https://doi.org/10.3758/s13423-011-0106-9>
- Townsend, J. T., Houpt, J. W., & Silbert, N. H. (2012). General recognition theory extended to include response times: Predictions for a class of parallel systems. *Journal of Mathematical Psychology*, 56(6), 476–494. <https://doi.org/10.1016/j.jmp.2012.09.001>
- Townsend, J. T., & Nozawa, G. (1995). Spatio-temporal Properties of Elementary Perception: An Investigation of Parallel, Serial, and Coactive Theories. *Journal of Mathematical Psychology*, 39(4), 321–359. <https://doi.org/10.1006/jmps.1995.1033>
- Wagenmakers, E.-J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., Selker, R., Gronau, Q. F., Dropmann, D., Boutin, B., Meerhoff, F., Knight, P., Raj, A., van Kesteren, E.-J., van Doorn, J., Smira, M., Epskamp, S., Etz, A., Matzke, D., ... Morey, R. D. (2018). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin and Review*, 25, 58–76. <https://doi.org/10.3758/s13423-017-1323-7>
- Wyble, B., Potter, M. C., Bowman, H., & Nieuwenstein, M. (2011). Attentional episodes in visual perception. *Journal of Experimental Psychology: General*, 140(3), 488–505. <https://doi.org/10.1037/a0023612>
- Yang, C.-T., Altieri, N., & Little, D. R. (2018). An examination of parallel versus coactive processing accounts of redundant-target audiovisual signal processing. *Journal of Mathematical Psychology*, 82, 138–158. <https://doi.org/10.1016/j.jmp.2017.09.003>

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.