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visual processing, up to the level of orthographic analysis. […] However, lexical access is serial' [4]. They support this claim with a compelling experiment showing that when given the time it takes to accurately identify one word, readers cannot accurately report the identities of two words [8]. This brings us back to the issue of word recognition. Similar to our Rapid Parallel Visual Presentation (RPVP) paradigm [9,10], the study of White *et al.* gauged conscious identification. Had we asked readers to report the identities of two words in the RPVP paradigm, they may well have failed to do so; and yet, the syntactic word-to-word constraints observed in that paradigm do suggest that there is a good deal of parallelism at play.

The lesson here is that the word recognition process should not merely be partitioned into sublexical (e.g., letter) processing and conscious identification. Prior to consciously identifying a word, the brain entertains tentative representations at various (intermediate) levels of processing (e.g., semantic features, syntactic structures), based on information from multiple words in the visual field. This is the key principle of cascaded processing (e.g., [10]), under which one does not need to identify a word in order to activate higher-order features. Rather, causality runs the opposite direction, with conscious identification being a mere product of this concert of activated representations, unfolding at various levels and fueled by input from multiple words. Whether conscious identification proceeds serially is not relevant.

We must highlight a related misconception. Schotter and Payne posit that 'just because word forms activate […] word candidates in parallel (i.e., 'hall' partially activates words like 'ball') en route to word identification, this does not imply that word identification simultaneously occurs across multiple words' [2]. That is an odd position to take. If one accepts that orthographic processing spans multiple words and that multiple word nodes are activated in parallel by a given orthographic input, then the only saving grace for serial processing is to assume that word nodes never reach a certainty threshold simultaneously. But the scope of this debate exceeds such mathematical matters.

Neurophysiological evidence reported by White *et al.* [11] provides more scientific sustenance. They found that when readers viewed two words simultaneously, with one of the words receiving an attentional cue, activation patterns in visual word form area-2 (VWFA-2) as registered with fMRI were influenced by the frequency of the cued word but not the other word. Meanwhile, VWFA-1 responded to the sublexical properties of both words, thus fueling the notion that parallel processed letter information is funneled into a serial bottleneck for conscious identification. However, as neurophysiological responses to word frequency are thought to reflect processing difficulty (e.g., [12]) rather than lexical activation *per se*, this might not have been the perfect predictor variable for testing parallel word processing. We would be interested to know if responses in VWFA-2 (or areas such as the left inferior prefrontal cortex, implicated in semantic processing) are modulated by the semantic congruency between words rather than the mere frequency of the second word (see Box 1). Regardless, set ups such as the one employed by White *et al.* [11] will undoubtedly advance our understanding of reading system's architecture greatly.

Finally, while verifications of our ideas in more natural settings are ongoing, it must be realized that knowledge about what the system is in principle capable of is already highly important for developing and testing sophisticated models of reading. As noted in our article, the OB1-reader model generates predictions both in a natural setting and in artificial settings. The latter provide a platform for concrete hypothesis testing. We therefore humbly disagree with Schotter and Payne's suggestion to avoid such paradigms; at worst, artificial settings offer a surplus of ways to falsify a theory. We have yet to encounter a serial model that can account for our 'artificially obtained' behaviors in addition to traditional text reading behaviors.

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Scientific Life

Preregistration Is Hard, And Worthwhile

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Preregistration clarifies the distinction between planned and unplanned research by reducing unnoticed flexibility. This improves credibility of findings and calibration of uncertainty. However, making decisions before conducting analyses requires practice. During report writing, respecting both what was planned and what actually happened requires good judgment and humility in making claims.

Preregistration of studies serves at least three aims for improving the credibility and reproducibility of research findings [1–3]. First, preregistration of analysis plans makes clear which analyses were planned *a priori* and which were conducted *post hoc*. This improves calibration of uncertainty for unplanned analyses, and diagnosticity of statistical inferences for planned analyses. Most often, planned analyses are equated with hypothesis testing or confirmatory research, but one can also preregister analysis plans when there are no *a priori* hypotheses to test (i.e., a planned exploratory analysis). Doing so has the benefit of strengthening statistical inferences as compared with unplanned analyses. Statistical tests always involve uncertainty: for example, at a criterion value of 5%, the presumed Type I error rate is 5%. However, this holds only if data meet the assumptions for a single statistical test. Undisclosed and unplanned analyses undermine the assumptions. Preregistration makes transparent the uncertainty of statistical tests by showing how many statistical tests were conducted and enabling an accurate familywise error rate.

Second, preregistration enables detection of questionable research practices such as selective outcome reporting [4] or hypothesizing after the results are known (HARKing; [5]). Third, preregistration of studies can reduce the impact of publication bias – particularly the prioritization of publishing positive over negative results – by making all planned studies discoverable whether or not they are ultimately published.

These benefits are evident with rapid growth in use of preregistration to improve research rigor [6]. However, preregistration is a skill that requires experience to hone. Getting the most out of preregistration requires practice because the previous training of many scientists has involved making some important design and analysis decisions during analysis [4,7]. Furthermore, while the dominant incentive structures of the scientific ecosystem promote intellectual defensiveness [8], preregistration may promote intellectual humility and encourage better calibration of scientific claims. With the accelerating adoption of preregistration, we now face the challenge of figuring out how to use this methodology to its fullest potential.

Preregistration Improves with Practice

It is common for researchers to begin a study with a general sense of how the methodology will be implemented; how the hypotheses will be tested; what exclusion rules will be applied; how variables will be combined; and which model form, covariates, and characteristics will be used. However, a general sense inevitably provides flexibility in making consequential decisions that could influence study execution, analysis, and reporting [9,10]. Effective preregistration requires converting that general sense into precise, explicit plans that anticipate what has not yet occurred and decisions about what will be done. For example, when collecting new data, how will you decide when to stop data collection? During analysis, what are the specific steps needed to examine the questions of interest? During authoring, what outcomes will be reported? Making these decisions before the data are available is challenging, especially the first time. It can also provide the jarring experience that decisions made earlier in one's career had been more data contingent than recognized. In preregistration, the common comfort of having the decision process unfold as one completes the analysis is converted to an uncomfortable mental simulation of what decisions will need to be made eventually. Moreover, research rarely goes precisely according to plan. Data collection can take longer than anticipated; a skewed data distribution may require adjustments to the planned analysis; unanticipated outliers may not be addressed by prespecified exclusion criteria. When the outcomes are known, the universe of contingencies is small; when the outcomes are unknown, the universe of contingencies is much larger.

Box 1. Getting Started with Preregistration

Articles providing conceptual and practical information about preregistration:

- 'A manifesto for reproducible science' Munafo *et al.*, 2017 [14]
- 'The preregistration revolution' Nosek *et al*., 2018 [6]
- 'An agenda for purely confirmatory research' Wagenmakers *et al.*, 2012 [3]
- 'Pre-registration in social psychology – a discussion and suggested template' van 't Veer and Giner-Sorolla, 2016 [2]

Registration workflows with relatively comprehensive guidance for decision-making:

- Clinicaltrials.gov: http://clinicaltrials.gov/
- OSF: http://osf.io/prereg/
- SREE: http://sreereg.icpsr.umich.edu/
- Declare Design: http://declaredesign.org/

Finding primers, help guides, and other resources:

- http://cos.io/prereg/

Preregistration requires research planning and it is hard, especially contingency planning. It takes practice to make design and analysis decisions in the abstract, and it takes experience to learn what contingencies are most important to anticipate. This might lead researchers to shy away from preregistration for worries about imperfection. Embrace incrementalism. Preregistration is a methodological skill that takes time to develop. Having some plans is better than having no plans, and sharing those plans in advance is better than not sharing them. With experience, planning will improve and the benefits will increase for oneself and for consumers of the research.

There are opportunities to accelerate that skill building. Study registries such as OSF (http://osf.io/prereg/) and SREE (https://sreereg.icpsr.umich.edu/), and decision tools such as Declare Design (http://declaredesign.org/) provide structured workflows to help researchers anticipate common decisions and provide guidance for articulating those decisions. Box 1 provides information on some helpful resources and guided workflows. The more comprehensive workflows provide guidance through each part of the study from stimuli selection and presentation, research design and manipulation, measure selection and use, data processing and management, primary and secondary analyses, and interpretation of results. Some evidence suggests that such workflows are effective in improving the specificity of preregistrations [11].

Other strategies for developing these skills include: (i) refining analysis plans by simulating data to practice making the decisions; (ii) splitting the real data into exploratory and confirmatory subsamples and preregistering the analysis after viewing the exploratory subset; (iii) drafting the study methods and results section in advance to help anticipate what should be done and how you will report it; and (iv) submitting the plan as a registered report for peer review to get expert feedback on the plan.

Researchers can embrace the common back-and-forth between planned and unplanned (confirmatory and exploratory) research activities and use *post hoc* analyses as an opportunity to learn, which facilitates better planning in the next investigation. Over time, the iterative experience between planning and resolving unplanned contingencies can be translated into documented, standard operating procedures that outline default design and analysis decisions [12]. In summary, there is value in unplanned discoveries despite their uncertainty and there is value in planned tests because of their diagnosticity. The key role of preregistration is to clarify which is which.

Transparently Reporting Deviations Helps Calibrate Confidence in Claims

Preregistration is a plan, not a prison (http://cos.io/blog/preregistration-plan-not-prison/). When deviations from the plan will improve the quality of the research, deviate from the plan. Many studies will have some deviations between the preregistered plan and what actually occurs. Planned analyses may contain errors or better approaches may emerge because of learning, discovery, and innovation. Obviously, deviations introduce risk. A seemingly trivial deviation might be highly consequential. For example, changing from a combined outcome variable to using just one component of the combination can inflate false positive risk [10]. Deviations inevitably make it harder to interpret with confidence what occurred in relation to what was planned. Transparency is key – all deviations from the plan should be acknowledged.

Reporting deviations from the plan can be challenging, especially because of journal word limits, pressures for narrative coherence, and reviewer expectations. If possible, report what occurs following the original plan alongside what occurs with the deviations, and share the materials, data, and code so that others can evaluate the reported outcomes and what would have occurred with alternative approaches. Transparency enables clarifying decisions across the research process, and facilitates others' understanding of justifications for those decisions.

Additional transparency strategies to maximize credibility of reported findings include: (i) when possible, update the preregistration with deviations before observing the data (e.g., fix errors in the analysis plan; add obvious exclusion rules that become apparent); (ii) mention all planned analyses, if only to explain why a planned analysis was not reported; (iii) include a table documenting and explaining all deviations; (iv) use supplements to share in full, not to hide inconvenient information; and (v) during analysis, actively log the decisions as they were made with rationales.

Intellectual Humility Improves Research Credibility

A successful program of research involves constantly striving to minimize error and misunderstanding while simultaneously recognizing that error and misunderstanding are inevitable. Research is hard, and scientists are fallible. Progress is made by identifying and addressing the shortcomings of yesterday's theories and methods to offer an improved understanding for tomorrow's skeptics to critique.

Preregistration can reveal the inevitable shortcomings of our research and consequently fosters intellectual humility. By embracing the fact that our present understanding is surely imperfect, identification of error presents an opportunity, not a threat. Preregistration provides opportunity for you and others to

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understand how you arrived at your claims. This means that you and others will be better positioned to find the weaknesses of what you planned and also identify ways to do it better the next time. Making the most of preregistration will require that we reduce the ego-driven desire to be right and cultivate the more productive truth-seeking desire to get it right [13].

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Spotlight

A Modeling Approach that Integrates Individual Behavior, Social Networks, and Cross-Cultural Variation

Paul E. Smaldino[1,*]

How do psychological traits shape social networks? How does this relationship influence the spread of behavior? In a recent paper, Muthukrishna and Schaller (*Pers. Soc. Psychol. Rev.*, 2019) use a modeling approach to explore these questions. In doing so, they illustrate the value of using a multilevel approach to study human behavior.

To understand the human mind and the behaviors it produces, we must appreciate that those minds – and the bodies to which they are attached – evolved, developed, and act in the context of their ecological and social environments. Thus, a complete cognitive science is necessarily integrated with the evolutionary, developmental, and social sciences. Formal models provide us with a way to handle this otherwise overwhelming complexity. They advance our ability to theorize: about distributed processing with connectionism, about social tradeoffs with game theory, and about the structure of interactions with network theory. These modeling frameworks allow us to better compartmentalize the components of complex systems, providing scaffolds for the development of richer theories.

All too often, psychological theories are described only at the level of individual processing. Muthukrishna and Schaller [1] (M&S) buck that trend. They present a model of how the distribution of individual cognitive features in a population can influence the structure of social networks and how that network structure may interact with other cognitive features to affect how opinions, behaviors, or norms may or may not spread (Figure 1). Individuals in their model have two psychological traits: 'extraversion', which controls the propensity to form social ties, and 'influenceability', which controls the propensity to change one's beliefs or behaviors in response to others. For both traits, M&S consider how individuals vary within a population, as well as how overall distributions of trait values can vary between populations.

Extraversion leads to the formation of social ties. Greater extraversion in a population is associated with denser networks, higher clustering, and shorter average path lengths. Individuals in the model are initialized to hold one of two possible behaviors (which can also be conceptualized