How Attention Controls Naming: Lessons From Wundt 2.0

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When models of the attentional control of vocal naming, applied to color-word Stroop and picture-word interference, were first computationally implemented and examined in 1990, an implementable model proposed by Wundt (1880, 1902) was not considered. Although these modern computer models, and more recent ones, clarify many aspects of the interference, most models fail to explain its time course, as outlined in Roelofs (2003). Wundt’s (1902) model assigns a key role to top-down inhibition, which is absent in most of the modern models. Here, an implementation of his model is presented, called Wundt 2.0. The necessity of perceptual inhibition was demonstrated by computer simulations of the interference and its time course, and supported by existing evidence from oscillatory brain activity in the alpha frequency band. Moreover, a new empirical study showed that Raven scores measuring the general intelligence factor g, discovered by Wundt’s student Spearman (1904), predict the magnitude of the Stroop effect in fast errors, in line with the model and evidence on alpha band activity. Also, the study provided evidence that response inhibition is absent during vocal naming in the Stroop task. To conclude, Wundt’s model has stood the test of time and provides a number of enduring lessons for our understanding of attention and performance.

Keywords: attentional control, inhibition, intelligence, modeling, naming

One hundred years ago, Wilhelm Wundt (1832–1920) passed away. Experimental psychology officially began, according to historical accounts (e.g., Benjamin, 2007; Boring, 1950), with the founding of his Institute for Experimental Psychology in Leipzig, Germany, in 1879. Inspired by the psychophysical discoveries of Weber and Fechner (e.g., Fechner, 1860) and Donders’ (1868) findings on reaction time (RT), Wundt began an extensive research program investigating the structure and operation of the mind, for which he received three Nobel Prize nominations. His legacy is huge, in terms of publications as well as number of students, but seems mostly forgotten (Fahrenberg, 2019). Reminiscences of Wundt by several of his American students (Hall et al., 1921) were about his supervision and the extraordinary range of his lectures, but not about his psychological theorizing integrating many areas. Blumenthal (1977) stated:

Quite literally, Wundt trained the first generation of American experimental psychologists; hence he may be counted as one of the major roots of American psychology. Yet in spite of this rather considerable contribution, it would appear today, in retrospect, that very little of Wundt’s actual system of psychology ever survived the return passage back across the Atlantic. (p. 13)

The present article is intended to revive part of Wundt’s theoretical legacy. He not only pioneered the study of interference on performance through RT experiments with a stimulus onset asynchrony (SOA) manipulation (Wundt, 1874), but also developed the first model of the attentional control of naming and reading (Wundt, 1880). The work on naming and reading RT by Wundt’s student Cattell (1886) was one of the inspirations for Stroop (1935) to create his color-word interference task. I present a computational implementation of Wundt’s model, called Wundt 2.0, and simulations with the model of the classic SOA curves of color-word Stroop interference obtained by Glaser and Glaser (1982) and replicated by many others. The SOA findings are a stumbling block for most of the modern implemented models of Stroop task performance. Wundt (1902) assigned a key role to top-down inhibition, which is lacking in most modern models. The simulations revealed the necessity of perceptual inhibition. The intended physiological interpretation of inhibition in the model is evaluated using existing findings on oscillatory brain activity in the alpha frequency band (8–13 Hz), which reflects inhibition.

I begin by briefly describing some relevant aspects of the legacy of Wundt. Next, his view on top-down control, the SOA findings on color-word Stroop interference, and the Wundt 2.0 implementation are described, and the results of the computer simulations are reported. I also report a new empirical study testing Wundt’s model. My critical examination of alternative theoretical models, including a systematic comparison of (historical) versions of Wundt’s model, supports a number of generalized lessons about how attention controls naming.
On the Legacy of Wundt

Wundt had one of the most tireless pens in the history of psychology, with a written output of about 53,735 pages of text (estimated by Boring, 1950). The 491 publications (nearly all of them in German) were compiled by his daughter Eleonore in 1927 (edited by Robinson, 2001). The early impact of Wundt’s research is shown by the fact that he was among the most frequently referenced authors in Woodworth’s (1938) classic Experimental Psychology, which summarizes the research of the first half century of the field. A major theoretical innovation of Wundt was his proposal that mental processes not only proceed via association, as had been the prevailing view for over two millennia (from Aristotle to Locke to Wernicke, 1874, and Müller, 1913), but also through a nonassociative mechanism, which he called apperception. Wundt assumed that apperception is underpinned by the prefrontal cortex of the human brain. The term apperception is no longer used but a similar contemporary notion is attentional control (also called executive or cognitive control; e.g., Blumenthal, 1975, 1976, 2001; Levelt, 2013). Wundt’s seminal contribution, however, is only rarely acknowledged in the modern literature (Fahrenberg, 2019).

Several of Wundt’s 188 doctoral students in Leipzig (Levelt, 2013; Tinker, 1932), Cattell, Külpe, Titchener, and Spearman among them, and their students such as Woodworth and Thorndike, performed important experimental and theoretical work (they were filmed for posterity between 1927 and 1933; watch Evans, 1970). Also, students initiated clinical psychology (Witmer), industrial and forensic psychology (Münsterberg), and intelligence tests (Cattell, Spearman). Moreover, they had an impact on professional organization and journals. For example, Cattell cofounded the American Psychological Association and psychology journals including Psychological Review, and he was the owner and editor of the journal Science for 50 years (Sokal, 1980). Cattell’s (1886) seminal RT studies on the naming of colors and reading their names in Wundt’s psychological laboratory laid the foundation upon which Stroop (1935) could design his color-word test half a century later, which is nowadays considered to be a gold standard of attentional measures (MacLeod, 1992).

From the second of the six editions of his book entitled Grundzüge der physiologischen Psychologie (Principles of Physiological Psychology) onward, Wundt described a detailed processing model for apperception in naming and reading (the first edition appeared in 1874, the second in 1880, and the sixth in 1908–1911). A corresponding woodcut figure (e.g., Figure 65 of Wundt, 1880, and Figure 105 of Wundt, 1902, shown later) displays a hierarchical network with subordinate processing centers (“untergeordneten Centren”) containing sensory, motor, and higher-level nodes for words, which are connected to nodes in a superordinate apperception center. Connections to (i.e., bottom-up), from, and within the subordinate processing network are excitatory, whereas top-down connections from the apperception center are excitatory (as proposed in the second, third, and fourth editions of the Grundzüge) or inhibitory (as proposed in the fifth and sixth editions). Apperception may optionally operate on sensory and corresponding higher-level nodes (i.e., perceptions), motor and corresponding higher-level nodes (i.e., responses), or both. As Wundt put it: “We then have, according as these impulses are transmitted to sensory or motor centers, either the apperception of sensations or the execution of voluntary movements”1 (Wundt, 1902/1904, p. 318, English translation by Titchener). Wundt’s descriptions seem detailed enough for a computational implementation although, to my knowledge, this has never been attempted.

Wundt (1902) presented his model as an alternative for the models of normal and impaired naming and reading of his contemporaries Wernicke (1874) and Lichtheim (1885) that lack top-down control mechanisms (Wundt, 1880, already applied the model to aphasia and acquired dyslexia, with reference to Kussmaul, 1877). Such control mechanisms are still missing from modern implemented psycholinguistic models, including the model of picture naming of Dell et al. (1997), the Lichtheim 2 model of Ueno et al. (2011), and the models of reading of Coltheart et al. (2001) and Seidenberg and McClelland (1989). These modern models address both normal and impaired language performance. Like the models of Wernicke and Lichtheim, each of the modern models can perform two or more tasks, such as picture naming and speech repetition (Dell et al.), naming, repetition, and word comprehension (Ueno et al.), and reading aloud and reading for comprehension (Coltheart et al., Seidenberg & McClelland). However, there are no top-down mechanisms within the models that achieve selective processing for one task or another, or that resolve interference when multiple stimuli are present, like hearing or seeing a word while naming a picture. Geschwind (1970) revived the model of Wernicke without including top-down control mechanisms. To my knowledge, the WEAVER++ model (e.g., Roelofs, 2003) is still the only implemented psycholinguistic model that contains top-down control mechanisms (see Roelofs, 2014a, for a neurocognitive version that is applied to impairments).

The model of Wundt exemplifies three claims: (a) An account of attention and performance requires a distinction between subordinate associative processes that lead from stimulus to response and superordinate apperceptive processes that regulate a wide variety of subordinate processes; (b) the superordinate processes employ inhibition (Wundt’s final statement on the regulative mechanism); and (c) subordinate processes may differ in strength or functional architecture, determining the amount of regulation required. Claims of other models differ, as explained later.

In what follows, a possible computational implementation of Wundt’s apperception model, Wundt 2.0, is described and applied to the Stroop effect and its time course. Eight model versions were examined that assumed either apperceptive enhancement or inhibition (see Pillsbury, 1908; Sikora & Roelofs, 2018), with inhibition applied to both the perceptual and response levels, the perceptual level only, or the response level only (see Broadbent, 1958; Roelofs, 2003), and with color naming differing from reading either in automaticity or functional architecture (see Brown, 1915; Cattell, 1886; Roelofs, 2003, 2008b). A systematic comparison of these assumptions using a single model has not been performed before. Computer simulations demonstrated that only the four versions of Wundt’s model that include perceptual inhibition (i.e., inhibition applied to both the perceptual and response levels or the perceptual level only) account for the time course findings, and

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1 “Je nachdem solche Impulse an Sinnes- oder Muskelnent übertragen werden, erfolgt dann entweder die Apperception von Empfindungen oder die Ausführung von Willensbewegungen” (Wundt, 1902, p. 524).
that one of these versions does best in light of other evidence. According to the model, apperception enables superordinate processes that regulate a wide variety of subordinate processes, including those underlying intelligence. I present the results of a new study that tested whether the general intelligence factor \( g \), discovered by Wundt’s student Spearman (1904), predicts the magnitude of the Stroop effect, in particular in fast errors, as implied by the model.

Modern evidence indicates that the engagement of top-down inhibition of perception is reflected in the amplitude of evoked oscillatory brain activity in the alpha frequency band. Alpha oscillations were discovered and dubbed by Berger (1929). The oscillations are nowadays obtained through high-density electroencephalography (EEG) and magnetoencephalography (MEG) recordings (for reviews, see Bengson et al., 2020; Jensen & Mazaheri, 2010; Klimesch, 2012; Mathewson et al., 2011; Piai & Zheng, 2019). These methods have high temporal resolution, which allows for assessing the timing of changes in oscillatory power, and their high sensor density provides for source localization in the brain. Jensen and Mazaheri (2010) stated: “From a physiological perspective the alpha activity provides pulsed inhibition reducing the processing capabilities of a given area.” As a consequence, “information is routed by functionally blocking off the task-irrelevant pathways: gating by inhibition.” (p. 1). When alpha power increases over a brain region its activation is decreased. Moreover, resting-state alpha band activity is correlated with measures of intelligence (e.g., Doppelmayr et al., 2002, 2005), including scores on the Raven test (Zakharov et al., 2020). Resting-state alpha power reflects individual differences in inhibitory ability. Wundt’s model is evaluated in light of the electrophysiological evidence.

A Model-Driven Research Program

Wundt’s central theoretical notion of apperception refers to active attentive as opposed to passive associative processing (e.g., Wundt, 1874, 1880, 1902). It concerns a modification of earlier notions of apperception advanced by Leibniz and Herbart (see Boring, 1950; Fahrenberg, 2019). A seminal psychological PhD thesis in Leipzig by Friedrich (1883), supervised by Wundt, aimed to estimate the duration of the apperception of colors and numbers. Wundt distinguished simple and complex apperceptive functions. The simple apperceptive functions are relating and comparing (“Beziehung und Vergleichung,” Wundt, 1896, p. 294) which are engaged, for example, in the psychophysical tasks of Weber and Fechner and the RT tasks of Donders (see Roelofs, 2018). The complex apperceptive functions are synthesizing and analyzing (“Synthese und Analyse,” p. 305), which are, in addition to the simple functions, specifically involved in more intellectual tasks, as used by Spearman. As Wundt (1902) put it:

If you want the complex phenomena, which are summarized under the indefinite collective name of “intelligence,” to be broken down into elementary processes, such that a clear and simple psychological notion can be connected to it, and possibly the relationship to an appropriately simple physiological correlate be made, such an elementary notion would be the apperception of a psychic content.” (p. 322, my translation)

In simple tasks like naming or reading, apperception is assumed to exert “a regulative influence” (“regulierenden Einfluss,” Wundt, 1902, p. 325) upon associative processes. Whereas Wundt (1880) took apperception to enhance (“verstärken,” p. 219) the subordinate spread of activation (“Erregung”), from Wundt (1902) onward, inhibition (“Hemmung,” p. 326) was assumed to be the mechanism. He stated that “the substrate of the simple apperception process may be sought in inhibitory processes which, by the very fact that they arrest other concomitant excitations, secure an advantage for the particular excitations not inhibited” (p. 317). Moreover, “the inhibitory influence, in this special case, is not exerted directly upon certain excitations in progress within the sensory centers, but rather upon the conduction of the excitations to the higher centers” (p. 317), achieving an inhibitory gate or filter. The apperceived perceptual content is foregrounded and other content is backgrounded in consciousness. In all editions of the Grundzüge, Wundt described in some detail how apperception works in the voluntary naming of a visual target among distractors. His proposal for the attentional control of perception is similar to Broadbent’s (1958) filter theory and Treisman’s (1964) attenuation theory, advanced 60 years later.

Wundt not only proposed the theoretical notion of apperception. He also experimentally examined it. Danziger (2001) stated:

The reaction time studies conducted during the first few years of Wundt’s laboratory constitute a unique early example of a coherent research program. . . . Wundt’s apperception concept provided a theoretical framework that transformed what would otherwise have been a collection of isolated studies. (p. 111)

Later experiments in the laboratory not only measured RTs but also made physiological recordings, including measurement of blood pressure, respiration, heart rate, and vasomotor responses (Wontorra, 2008). Moreover, in the lab, Kraepelin (1883) studied the influence of psychoactive drugs on simple, choice, and go/no-go RTs. The multimethod approach characterizes Wundt’s research strategy (Fahrenberg, 2019). EEG recording and computational modeling did not yet exist.

A picture from a photo shoot that took place around 1912 shows Wundt, about 80 years old, surrounded by collaborators (reprinted in Benjamin, 2007, and several other history books). Wundt pretends to be engaged in a choice RT experiment (see Donders, 1868), holding a right-hand finger on one button and a left-hand finger on another button. In the background is a poster with RT data. To demonstrate the effect of apperception on processing, the poster shows frequency distributions of RTs in three conditions, illustrated in Figure 1 (I reconstructed the curves on the basis of

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several pictures from the photo shoot).\textsuperscript{5} The horizontal axis represents the RTs and the vertical axis their frequency. Wundt (1918a) described how the distributions come about, based on insights from experiments by his doctoral students Lange (1888) and Alechsieff (1900).

Suppose a participant has to perform a simple RT task (see Donders, 1868), for example, to press a button when hearing a tone. If this task is performed for many stimulus presentations, for example 500 trials, the frequency distribution of the RTs may be plotted. According to Wundt (1918a), the “natural” distribution consists of a mixture of reflexive (“muscular”) reactions and apperceptive reactions with attention paid to the stimulus (“sensorial”). In the case of muscular reactions, apperception is used to fully prepare the motor response before trial onset (i.e., in terms of Wundt’s model, this involves apperception of motor and corresponding higher-level nodes), whereas in the case of sensorial reactions, apperception is used to prepare a perceptual image of the expected stimulus (i.e., in terms of his model, this involves apperception of sensory and corresponding higher-level nodes). If the participant is asked to respond for another 500 trials, the reflexive reactions will dominate, and the frequency distribution curve will shift leftward to shorter RTs (i.e., indicating that shorter RTs now have a higher frequency). However, if the participant receives the instruction to pay attention to the stimulus and only respond when the tone is fully identified, then apperception will be involved. As a consequence, the sensorial reactions will dominate, and the frequency distribution curve will shift rightward to longer RTs (i.e., indicating that longer RTs now have a higher frequency).

Delorme et al. (2007) examined Wundt’s distinction between muscular and sensorial reactions in an EEG study by looking at oscillatory brain activity. They observed that more reflexive manual responses are preceded by increased activity in the theta frequency band (4–7 Hz) arising in medial prefrontal cortex.

To summarize, Wundt’s empirical research was guided by his theory of apperception, which encompassed simple functions like relating and comparing as well as complex functions like synthesizing and analyzing. Moreover, for the attentional control of naming and reading, Wundt initially assumed top-down enhancement and later top-down inhibition. Apperception was investigated using several methods, including physiological measurements and examinations of RT distributions, which have also been used in testing Wundt 2.0 in the present article.

\textbf{The Time Course of the Stroop Effect in Naming and Reading}

Wundt (1874) initiated the study of interference by means of RT experiments with an SOA manipulation. In particular, he conducted an experiment that examined the influence of a distractor tone (“störender Klang,” p. 748) on the RT of manually responding to a target tone (“Haupteindruck”). A manipulation of the SOA (the exact SOA is not reported) allowed for an investigation of the time course of interference. Wundt observed that the RT was longer with distractor preexposure (“vorher”) than postexposure (“nachher”) or simultaneous presentation (“gleichzeitig”).

As a student in Wundt’s laboratory in Leipzig in the 1880s, Cattell ran many RT experiments and made a number of seminal observations on the speed of naming pictures, colors, letters, and words (e.g., Cattell, 1886). For example, he observed that naming pictured objects and colors takes more time than reading the corresponding words or reading letters. According to Cattell, this is because “in the case of words and letters the association has

\textsuperscript{5} There are actually two graphs on the poster. An upper graph is labeled “Muskulärer Typus” (muscular type), which I reconstructed and show in Figure 1, and a lower graph (not shown) is labeled “Sensorieller Typus” (sensorial type), with similar RT patterns. The types refer to individual differences in tendency (“Neigung”) to react reflexively or with more deliberation. According to Wundt (1918a), practice and instruction have the same effect on the RT frequency distributions across these individual tendencies, which is what the two graphs on the poster demonstrate.
taken place so often that the process has become automatic, whereas in the case of colors and pictures we must by a voluntary effort choose the name” (p. 65). Stroop (1935) exploited the difference in RT between naming and reading in his color-word experiments.

In modern computerized versions of the Stroop test, participants are instructed to vocally name the presentation color of printed incongruent or congruent color words (e.g., the words green or red printed in red ink; say “red”) or the color of a neutral row of Xs. Performance is typically worse (i.e., mean RT is typically longer and accuracy is lower) on incongruent than on neutral trials, descriptively called interference, and performance is often better (i.e., RT is shorter and accuracy higher) on congruent than on neutral trials, descriptively called facilitation. In reading aloud color words, incongruent and congruent presentation colors do not have an effect. Thus, whereas words influence color naming, colors do not affect word reading, which is called the Stroop asymmetry (see MacLeod, 1991, for a review).

MacLeod et al. (2003) noted that Stroop interference “is often referred to in the literature as “Stroop inhibition,” conflating phenomenon and explanation” (p. 181). To distinguish explanandum and explanans, I use the term interference to indicate that RT is longer and accuracy is lower in one condition than another and the term inhibition to refer to a mechanism of top-down control involving the suppression of processing.

In the “definitive pair of studies” (MacLeod, 1991, p. 180), Glaser and Glaser (1982) examined Stroop interference and facilitation in both color naming and word reading by presenting words and colors at a wide range of distractor preexposure SOAs (henceforth indicated by a minus sign) and postexposure SOAs. One group of participants had to name the colors and another group had to read aloud the words. The words were presented in white on a dark background and the colors were presented as colored rectangles. The SOAs ranged from -400 ms distractor preexposure to 400 ms postexposure, with values differing by 100 ms.

The left-most panel of Figure 2 displays the empirical results of Glaser and Glaser (1982). Shown are the RT differences between the incongruent and neutral conditions, and between the congruent and the neutral conditions, as a function of SOA in color naming and word reading. Interference by incongruent words in color naming increased as the preexposure time of the word decreased. The interference at SOA = -400 ms (i.e., 25 ms) was about half of that at SOA = -100 ms (45 ms) and about a third of that at SOA = 0 ms (72 ms). Congruent words yielded a rather flat pattern of facilitation, ranging from 31 ms at SOA = -400 ms to 30 ms at SOA = -100 ms. For word reading, no interference and

Figure 2
Empirically Observed and Simulated Time Courses of the Stroop Effect

Note. MAE = mean absolute error, which is the average of the absolute differences in milliseconds (ms) between simulated and empirical effects in color naming and word reading.
facilitation effects were obtained at any SOA. That is, there is no reverse Stroop effect, as MacLeod (1991) called it (i.e., no effect of colors on reading). Word reading was about 100 ms faster than color naming. Later studies have replicated these findings on the interference and facilitation effects in naming and reading (e.g., Glaser & Glaser, 1989; Long & Lyman, 1987; Roelofs, 2010b, 2014b), not only within but also between languages (Roelofs, 2010a). Also, the same patterns of results are obtained with color rectangles and auditory words (Roelofs, 2005). Moreover, the patterns are replicated with the picture-word analog of the color-word Stroop test (e.g., Damian & Martin, 1999; Glaser & Düngehoff, 1984; Rayner & Springer, 1986; Schriefers et al., 1990; Starreveld & La Heij, 1996), discussed later.

In 1990, the first computationally implemented models of color-word Stroop naming and reading were published (i.e., Cohen et al., 1990; Phaf et al., 1990), without reference to Wundt’s work. The models were applied to the evidence on the time course of the Stroop effect, in particular, the SOA curves obtained by Glaser and Glaser (1982). Although these models were successful in clarifying several findings on Stroop test performance, they failed to explain key aspects of the time course of the Stroop effect (for extensive discussion, see Roelofs, 2003, 2010b). This also holds for models that were developed more recently (e.g., Cohen & Huston, 1994; Stafford & Gurney, 2007). Figure 2 also shows the time course of the Stroop effect in color naming and word reading in simulations performed by Cohen et al. and Phaf et al. themselves using their models.

The model of Cohen et al. (1990) assumes a feedforward activation network consisting of separate input and intermediate nodes for color naming and word reading, and shared output nodes connected to evidence accumulators. The word reading pathway has stronger connections than the pathway for color naming to reflect the assumption that reading is more highly practiced and therefore more automatized than color naming, making reading faster than naming. This corresponds to what Cattell (1886) assumed. Attentional control is achieved by task nodes connected to the intermediate nodes for color naming and reading, which enhance activation in one of the pathways, depending on the task. Evidence for one response versus the other accumulators exceeds a threshold. As Figure 2 shows (derived from Figure 7B of Cohen et al.), the model does not capture the time course of the Stroop effect. In the model, evidence for the response to the distractor word accumulates more with increasing preexposure SOA, yielding larger effects, unlike what is empirically observed for color naming. Moreover, the model incorrectly yields a reverse Stroop effect in word reading.

The failure of the model of Cohen et al. (1990) to capture the time course of Stroop interference in color naming (i.e., to capture the empirically observed increase of interference with decreasing word preexposure SOA) reflects the mechanism of top-down control (i.e., enhancement) in the model rather than its parameter values. Increasing or decreasing the strength of top-down control in the model influences the magnitude of interference while preserving the shape of the SOA curve (i.e., interference remains constant at preexposure SOAs). After word input, a stable state of activation is quickly reached, yielding constant interference. Moreover, the model yields a reverse Stroop effect in word reading.

The failure of the model of Phaf et al. (1990) to capture the time course of Stroop interference in color naming (i.e., to capture the empirically observed increase of interference with decreasing word preexposure SOA) reflects the mechanism of top-down control (i.e., enhancement) in the model rather than its parameter values. Increasing or decreasing the strength of top-down control in the model influences the magnitude of interference while preserving the shape of the SOA curve (i.e., interference remains constant at preexposure SOAs). In discussing parameter values, Phaf et al. stated:

The parameter values (i.e., connection weights) used in all simulations were obtained in an initial trial and error process. The search for an adequate parameter set was guided by the desire to obtain a good qualitative fit. Before performing the simulations reported here the exact parameter values were derived by fitting the simulation results quantitatively to the experimental results of a single experiment. (Exp. I, Glaser & Glaser, 1982; p. 288)

Thus, the parameter values of the model of Phaf et al. were chosen to be optimal for quantitatively fitting the data of Glaser and Glaser (1982) on Stroop color naming and word reading displayed in Figure 2. To conclude, the discrepancy between
empirical data and model is attributable to the assumed attentional mechanism rather than to the parameter values, which were optimized.

Computer simulations by Cohen and Huston (1994) and Stafford and Gurney (2007) showed that their models yield SOA curves similar to those of Phaf et al. (1990). The model of Stafford and Gurney combines the network of Cohen et al. (1990) with a mechanism that initially inhibits all responses and later disinhibits the response for which most evidence has been accumulated. Computer simulations by Stafford and Gurney revealed that their model yields constant interference in color naming of about 75 ms at all SOAs ranging between −2,000 ms and −200 ms.

In Roelofs (2003), I presented an alternative account for the Stroop effect, based on the psycholinguistic WEAVER++ model of spoken word production (e.g., Levelt et al., 1999). In addition to the top-down enhancement of target processing that is assumed by Cohen et al. (1990) and Phaf et al. (1990), I assumed reactive blocking of distractor perception and selection of a target response through condition-action rule application. Perceptual inhibition is absent in the models of Cohen et al. and Phaf et al., and also in the model of Stafford and Gurney (2007). Moreover, I maintained that perceived words are more directly linked to their responses than are colors, thus assuming an architectural difference (Brown, 1915; Phaf et al.), rather than greater automaticity of reading than color naming (Cattell, 1886; Cohen et al.). Figure 2 shows that the WEAVER++ model captures the time course of the Stroop effect. Interference from incongruent words in naming increases with decreasing preexposure SOA and facilitation from congruent words, thus assuming an architectural difference (Brown, 1915; Phaf et al.), rather than greater automaticity of reading than color naming (Cattell, 1886; Cohen et al.).

Figure 2 also displays the mean absolute error (MAE) for the models of Cohen et al. (1990), Phaf et al. (1990), and Roelofs (2003), which is the average difference in ms between the simulated and empirical effects. The MAE is simpler and more directly interpretable than the commonly used root mean square error (Willmott & Matsuura, 2005). The MAE in the figure indicates the quantitative goodness of fit between the model and the naming and reading data of Glaser and Glaser (1982), with a higher MAE denoting a worse fit. The MAE is highest for the model of Cohen et al. and lowest for my own model.

Other implemented models of Stroop task performance (i.e., Melara & Algomo, 2003; Kalanthroff et al., 2018) have not been applied to the time course data, or they also successfully capture the findings (Chuderski & Smolen, 2016). These models are discussed later.

**Wundt’s Model Applied to the Stroop Task**

Figure 3 illustrates Wundt’s “neurocognitive” model (adapted from Figure 105 of Wundt, 1902). The left panel shows a network with visual (VC, “Sehzentrum”) and auditory (AH, “Höreinsenbrum”) input nodes, intermediate optical nodes (O, “optisches Sprachzentrum”), auditory nodes (A, “akustisches Sprachzentrum”), articulation nodes (L, “motorisches Sprachzentrum”), and writing nodes (B, “Zentrum der Schreibbewegungen”) for language, and motor output nodes (MC, “direktes motorisches Zentrum”) for writing and speech articulation, which are all connected to nodes in an apperception center (AC). Wundt rejected precise localization but coarsely localized the visual input nodes in occipital cortex, the intermediate word nodes in left peri-sylvian regions of the human brain including Broca’s and Wernicke’s areas, and the apperception center in prefrontal cortex. According to Wundt, the apperception center integrates motivational, emotional, cognitive, perceptual, and motoric signals (similar to Dehaene, 2014, and Meyer & Kieras, 1997). Connections to, from, and within the processing network are excitatory, whereas top-down connections from the apperception center are excitatory (e.g., Wundt, 1880) or inhibitory (e.g., Wundt, 1902). In oral naming of a visual stimulus a in the context of distractors b, c, and d, the stimuli activate visual input nodes and activation spreads to corresponding intermediate nodes for words. Moreover, in parallel, the apperception center is activated, which enhances the activation spread between the nodes for the target a (Wundt, 1880) or inhibits the activation spread between the nodes for the distractors b, c, and d (Wundt, 1902), so that an articulatory motor response for a may be produced.

In all editions of his *Grundzüge*, Wundt argued that this model, as shown in the left panel of Figure 3, is simplified in several respects. First, the strength of the individual connections may vary depending on practice. Second, the nodes for visual words in O are presumably directly connected to the articulation nodes in L rather than indirectly via auditory nodes in A (i.e., an architectural difference), as illustrated in the right panel of Figure 3. Third, the representation of words by O, A, and L nodes is simplified compared with Wundt’s (1900) own psycholinguistic treatment of words in *Die Sprache* (Language), which is also true in light of modern models of spoken word planning (e.g., Levelt et al., 1999).

The right panel of Figure 3 shows an application of the model to the color-word Stroop test (the example stimulus is a red color patch with the word *green* superimposed), where R and G stand for representations of the colors red and green, respectively, and g and G for the corresponding words. Colors and visual word forms are processed in different areas of the occipital-temporal cortex of the brain (e.g., Gazzaniga et al., 2002). Apperceptive enhancement or inhibition may concern the spread of activation between the word area, or the color area, and connected higher-level processing areas, depending on the task. The target and distractor nodes at each level may be determined by the apperceptive function of relating, and response selection (i.e., selection of the appropriate node in L) may happen after comparing activation levels. Wundt (1896/1897) stated:

The most elementary apperceptive function is the relating of two psychical contents to each other. . . . For example, when we recognize the identity of an object with one perceived before, or when we are conscious of a definite relation between a remembered event and a present impression, there is in both cases a relating apperceptive activity connected with the associations.6 (p. 250)

I assume that the appropriate response node in L is determined by first relating node R (for naming the color red) or g (for reading the

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6 “Die elementarste aller Functionen der Apperception ist die Beziehung zweier psychischer Inhalte auf einander. . . . Wenn wir uns z. B. bei einer Wiedererkennung der Identität des Gegenstandes mit einem früher wahrgenommenen, oder wenn wir uns bei einer Erinnerung einer bestimmten Beziehung des erinnerten Erlebnisses zu einem gegenwärtigen Eindruck bewusst werden, so verbindet sich hier mit den Associationen zugleich eine Funktion der Apperception in Gestalt beziehender Thätigkeit” (Wundt, 1896, p. 294).
word green in SC to the associated node in O (i.e., R for naming or g for reading), then the node in O to the associated node in A (i.e., the verbal node r for naming or g for reading), and finally the node in A to the associated node in L (i.e., the verbal node r for naming or g for reading). Through the relating function, the apperception center knows which activation spread between nodes along the way to enhance (Wundt, 1880) or to inhibit (Wundt, 1902), similar to the verification function proposed by Roelofs (2003). Moreover, I assume that the determined L node (i.e., r for naming or g for reading) is selected if its activation exceeds a critical difference with respect to the L node activated by the distractor (i.e., g in naming or r for reading), which may be determined by the apperceptive function of comparing. As Wundt stated: “Every psychical element and every psychical compound . . . constitutes a psychical quantity. A determination of the value of such a quantity is possible only through its comparison with some other quantity of the same system” (1897, p. 252).

Next, I describe my computational implementation, Wundt 2.0, and report the results of simulations of the time course of Stroop color naming and reading. It should be noted that a computational implementation always goes beyond a verbal model and that Wundt might not have approved of the implementation. Thus, at most, my implementation may provide a proof of concept of Wundt’s ideas. Eight model versions were examined, listed in Table 1. The versions assumed either apperceptive enhancement (Wundt, 1880) or inhibition (Wundt, 1902), but not both, with inhibition applied to both the perceptual and response levels, the

Note. Solid lines denote “centripetal” connections and dashed lines “centrifugal” connections. The top-down connections from the apperception center (AC) are excitatory (Wundt, 1880) or inhibitory (Wundt, 1902), while all other connections are excitatory. Greek letters from the original figure (left) have been replaced by Latin letters, and the eye, ear, and mouth have been added to denote the sensory and motor organs (a hand for writing is omitted). SC = seeing center; HC = hearing center; MC = motor center; O = optical; A = auditory; L = articulation; B = writing; r = word red; g = word green; R = color red; G = color green.

Footnotes:
7 “Jedes psychische Element und jedes psychische Gebilde ist . . . eine psychische Größe. Eine Auffassung des Werthes einer solchen Größe ist aber nur dadurch möglich, dass dieselbe mit andern Grössen desselben Continuums verglichen wird” (Wundt, 1896, p. 294).
8 In Wundt 2.0, I have strictly followed Wundt’s own statements about enhancement and inhibition in the various editions of the Grundzüge. In the second edition (Wundt, 1880, pp. 218–224), third edition (Wundt, 1887, pp. 234–241), and fourth edition (Wundt, 1893, pp. 230–235), Wundt proposed that the top-down apperceptive function is one of enhancement (inhibition is not mentioned at all), whereas in the fifth edition (Wundt, 1902, pp. 322–327) and sixth edition (Wundt, 1908, pp. 382-385), he proposed that the function is one of inhibition. Enhancement was explicitly rejected. For example, he stated: “The assumption of such an inhibition process makes it understandable that apperception does not in itself consist in an enhancement of the sensory content” (Wundt, 1908, p. 382, my translation “Die Annahme eines solchen Hemmungsganges macht daher begreiflich, dass die Apperzeption an sich nicht in einer Verstärkung der Empfindungsinhalte besteht”).
perceptual level only, or the response level only (see Wundt, 1902, 1918a), and with naming and reading differing in either automaticity or functional architecture (see Wundt, 1880, 1902). Inhibition applied to irrelevant perceptions implies an early locus of attentional selectivity (see Broadbent, 1958; Treisman, 1964). Inhibition not applied to irrelevant perceptions but to responses implies a late locus of selectivity (see Deutsch & Deutsch, 1963). After reporting the simulation results, I discuss these assumptions in light of other evidence in the literature, addressing issues in the modern study of attention and performance.

Method

The processing network in the simulations consisted of input nodes for the colors red and green (i.e., R and G) and for the visual words red and green (i.e., r and g) in SC, corresponding nodes in O, and nodes for the words red and green (i.e., r and g) in A and L, as illustrated in the right panel of Figure 3. The auditory sensory nodes in HC, the intermediate word nodes in B for writing, and the MC nodes were not implemented. All connections were bidirectional, except for the direct connections between O and L assumed by the architecture versions of the model (versions #2, #4, #6, and #8), explained later. Activation spread in millisecond time steps \( \Delta t \) through the network according to the following equation with spreading rate \( r \) and decay rate \( d \),

\[
a(m, t + \Delta t) = a(m, t)(1 - d) + \sum_n r(a(n, t))
\]

The rate \( r \) indicates the strength of the connection between node \( m \) and another node \( n \), \( a(m, t) \) and \( a(n, t) \) indicate their levels of activation at time \( t \), and \( \sum_n r(a(n, t)) \) denotes the internal input to node \( m \). The choice for this activation function was based on its simplicity and the fact that it does a good job in other models of naming (e.g., Dell et al., 1997; Levelt et al., 1999; Roelofs, 2003).

The simulations started by providing external input activation to the input nodes in SC with the appropriate SOA, followed by a spread of activation through the network. After a relating time required for the determination of the target node in L, this node was selected as response if its activation exceeded a critical difference relative to the other node. Following target onset (i.e., color or word, depending on the task), enhancement of the input to each of the target nodes (model versions #1 and #2) occurred after an apperception latency with a particular strength. For example, enhancement with a strength of 3.5 involved multiplying the external input to the SC nodes and the subsequent internal input to the O, A, and L nodes of the target by 3.5. Alternatively, in case of response competition, inhibition of the input to the response node for the distractor in L (versions #3, #4, #7, and #8) occurred after an apperception latency with a particular strength following the determination of the target node in L (i.e., competitor response nodes cannot be inhibited before the target node is known). In addition (versions #3 and #4) or alternatively (versions #5 and #6), following distractor onset (i.e., word or color, depending on the task), inhibition of the input to the perceptual nodes of the distractor occurred after an apperception latency and with a particular strength (versions #3–#6). For example, perceptual inhibition with a strength of 0.05 (−95%) involved multiplying the input to the SC and O nodes by 0.05. Enhancement or inhibition was applied serially with the apperception latency to the inputs to SC, O, A, and L nodes. The relating time and apperception latency for reading were half those for naming to reflect their difference in automaticity or architecture. In Wundt 2.0, each word is represented by connected SC, O, A, and L nodes, but the nodes of different words are not connected. Wundt was not clear about whether and how exactly different words are connected, and such connections are also not needed for simulating Stroop interference and facilitation. Therefore, I have implemented the simplest case, which consists of omitting connections between different words. This also implies that the model may be scaled up (e.g., the whole color vocabulary of English may be included) without influencing its behavior.

The values of the parameters \( r, d \), and external input were the same as in the model of Roelofs (2003). These parameters concern the subordinate processes that map colors and words onto their vocal responses. The relating time for L was set to 200 ms, which is the lower boundary that has been estimated for response selection in picture and color naming (Indefrey, 2011). The values of the other parameters (i.e., the strength of reading relative to naming, the critical difference in activation for response selection, and the apperception strength and latency) were obtained through a grid search, that is, an exhaustive search through the parameter space. The search aimed to obtain the combination of parameter values for each model version that minimizes the MAE measure of fit between the simulated effects and the empirical effects obtained by Glaser and Glaser (1982) for Stroop color naming and reading.

Table 2 gives the parameter values that were common between the model versions. The MAE and the optimal values of the apper-
ception latency and strength parameters are given when discussing each model version.

The first model version (#1) implemented the assumptions that apperception involves enhancement of the activation spread between target nodes at all processing levels and that color naming and word reading differ in automaticity (i.e., strength). The latter assumption is plausible in light of Wundt’s claim that connection strength varies with amount of practice, although he did not make this assumption specifically for naming and reading. Yet if no difference between naming and reading is assumed, the Stroop interference and facilitation effects will be the same in naming and reading (i.e., there will be no Stroop asymmetry), contrary to the empirical data. Therefore, the first model version (#1) assumed a difference in strength, whereas the second version (#2) assumed an architectural difference, in line with Wundt’s own psycholinguistic model (see Figure 104 of Wundt, 1902, extensively discussed by Levelt, 2013). In his psycholinguistic model, Wundt assumed that the direct connection runs from O to L nodes but not vice versa (i.e., feedforward only), which was also assumed in the simulation. The third and fourth model versions assumed that apperception involved inhibition applied to both the perceptual level (i.e., SC and O) and the response level (i.e., L), while differing in the assumption of reading automaticity (#3) versus an architectural difference (#4). The fifth and sixth model versions assumed apperceptive inhibition of perception only (i.e., SC and O), while assuming reading automaticity (#5) or an architectural difference (#6), and the seventh and eighth model versions assumed apperceptive inhibition of responses only (i.e., L), while differing in reading automaticity (#7) or architecture (#8).

The simulations were coded and run using the C programming language and the programming environment of Microsoft Visual Studio, 2017. The source code of the simulations is available from the archive of the Open Science Framework (Roelofs, 2020).

**Results**

Figure 4 displays the simulation results for the two model versions (i.e., #1 and #2) with enhancement (Wundt, 1880). Enhancement means that the external input to the SC nodes and the subsequent internal input to the O, A, and L nodes of the target was increased multiplicatively (the strength parameter) after a certain time (the latency parameter) following target stimulus onset (i.e., color or word, depending on the task). The estimated optimal values of the strength and latency parameters are shown in the figure, along with the MAE measure of fit between each model version and the naming and reading data of Glaser and Glaser (1982, shown in Figure 2).

Figure 4 shows that the patterns of effects are similar for the two model versions. In both cases, interference from incongruent words in color naming increases with increasing preexposure SOA, as in the model of Cohen et al. (1990), but unlike the empirical data. In the Wundt 2.0 model, activation of the response to the distractor word builds up longer as the preexposure SOA increases, which yields larger interference. There is no facilitation by congruent words in the model. Moreover, at long preexposure SOAs, there is some interference from incongruent colors on word reading in model version #2. These outcomes for naming and reading clearly do not correspond to the classic empirical data of Glaser and Glaser (1982, see Figure 2). The simulation outcomes demonstrate that apperceptive enhancement does not account for the time course of the Stroop effect.

Figure 5 displays the simulation results for the model versions with inhibition applied to both the perceptual and response levels (#3 and #4) or to the perceptual level only (#5 and #6), which are both options according to Wundt (1902). Perceptual inhibition means that the external input to the SC nodes and the subsequent internal input to the O nodes for the distractor was decreased multiplicatively (the strength parameter) after a certain time (the latency parameter) following distractor onset. Response inhibition means that, in case of response competition, the internal input to the L node for the distractor was decreased multiplicatively (the strength parameter) after a certain time (the latency parameter) following the determination of the target response in L. The estimated optimal values of the strength and latency parameters are shown in the figure, along with the MAE measure of fit between each model version and the naming and reading data of Glaser and Glaser (1982, shown in Figure 2).

Figure 5 shows that the patterns of effects are similar for the four model versions. Interference from incongruent words in color naming increases with decreasing preexposure SOA, whereas facilitation remains constant at preexposure SOAs. In word reading, there is some interference for the automaticity versions #3 and #5. These patterns of effects for naming and reading generally agree
with the empirical data of Glaser and Glaser (1982, see Figure 2), except for the effects on reading in the automaticity versions. The simulation outcomes demonstrate that apperceptive inhibition of distractor perception accounts for the time course of the Stroop effect, regardless of the presence of response inhibition.

Figure 6 displays the simulation results for the model versions with inhibition applied to the response level only (#7 and #8), which is also an option according to Wundt (1902). As indicated, response inhibition means that, in case of response competition, the internal input to the L node for the distractor was decreased multiplicatively (the strength parameter) after a certain time (the latency parameter) following the determination of the target response in L. The estimated optimal values of the strength and latency parameters are shown in the figure, along with the MAE measure of fit between each model version and the naming and reading data of Glaser and Glaser (1982, shown in Figure 2). Note that a strength parameter of 0.0 (–100%) means that apperceptive inhibition had maximal strength in that it fully blocked input to the L node of the distractor.

Figure 6 shows that the patterns of effects are similar for the two model versions. In both cases, interference from incongruent words in color naming increases with increasing preexposure SOA, as in the model of Cohen et al. (1990), but unlike the empirical data. In the model, activation of the response to the distractor word builds up longer as the preexposure SOA increases, which yields larger interference. There is no facilitation by congruent words in the model. Also, there is some interference and facilitation in word reading. These outcomes clearly do not correspond to the empirical data of Glaser and Glaser (1982, see Figure 2). The simulation outcomes demonstrate that apperceptive inhibition of responses only does not account for the time course of the Stroop effect.

The goodness of fit between model and the naming and reading data of Glaser and Glaser (1982) was better for versions #3–#6 with perceptual inhibition (MAE ~ 9 ms) than for versions #1 and #2 with enhancement (MAE ~ 16 ms) and versions #7 and #8 with response inhibition only (MAE ~ 21 ms). Thus, the versions with perceptual inhibition not only best capture the shape of the SOA curves, but they are also numerically closest to the empirically observed effects.

The optimal values of the parameters of each version of the Wundt 2.0 model were obtained through a grid search. Importantly, examinations of the range of what each model version could cover with different parameter values revealed that the RT patterns do not depend on the exact parameter values. Changing the parameter values generally leads to expected changes in the patterns.
of RT effects, changing their magnitude while preserving the shape of the curves. In particular, decreasing the strength of inhibition or enhancement increases Stroop interference; decreasing the critical difference for response selection decreases interference; decreasing the apperception latency also decreases interference.

Figure 7 illustrates how changing the value of the apperception latency parameter influences the magnitude of Stroop interference in each model version. For the apperception strength parameter, the optimal value was used for each version. In all model versions, increasing the apperception latency increases interference while preserving the shape of the SOA curve. In the enhancement model versions (#1 and #2), interference from incongruent words in color naming increases with increasing preexposure SOA, regardless of the exact value of the latency parameter. In the model versions with perceptual inhibition (#3–#6), interference increases with decreasing preexposure SOA, regardless of the exact value of the latency parameter. Finally, in the model versions with response inhibition only (#7 and #8), interference increases with increasing preexposure SOA, regardless of the exact value of the latency parameter.

Figure 8 illustrates how changing the value of the apperception strength parameter influences the magnitude of Stroop interference in each model version. For the apperception latency parameter, the optimal value was used for each version. In all model versions, decreasing the apperception strength increases interference while generally preserving the shape of the SOA curve. In the enhancement model versions (#1 and #2), interference from incongruent words in color naming increases with increasing preexposure SOA, regardless of the exact value of the strength parameter. In the model versions that include perceptual inhibition (#3–#6), interference increases with decreasing preexposure SOA, regardless of the exact value of the strength parameter. However, at low strength, interference increases especially with distractor preexposure, which causes the effect to be constant across preexposure SOAs. This influence is present for all four versions, which indicates that it is attributable to the diminished strength of perceptual inhibition (which is common to versions #3–#6). Finally, in the model versions with response inhibition only (#7 and #8), interference increases with increasing preexposure SOA, regardless of the exact value of the strength parameter.

To summarize, changing the value of the apperception latency or strength parameters does not allow the model versions with enhancement (#1 and #2) or with response inhibition only (#7 and #8) to capture the characteristic increase of interference with decreasing preexposure SOA that is empirically observed (Glaser & Glaser, 1982, see Figure 2). The characteristic shape is outside the range of what these model versions could cover with different parameter values. In contrast, the model versions that include perceptual inhibition (#3–#6) capture the characteristic shape across a range of parameter values. To conclude, the model versions with enhancement (#1 and #2) and with response inhibition only (#7 and #8) fail to capture the time course of the Stroop effect due to their apperception mechanism rather than the parameter values.

Discussion

The simulations demonstrate that the model versions with enhancement only (i.e., #1 and #2) or with response inhibition only (i.e., #7 and #8) do not capture the empirical findings on the SOA effects, whereas the model versions with inhibition to both the perceptual and response levels (i.e., #3 and #4) or to the perceptual level only (i.e., #5 and #6) generally agree with the data. This provides converging evidence for a general lesson: To account for the SOA effects in Stroop test performance, perceptual inhibition needs to be assumed. Models without such perceptual inhibition, like the enhancement versions of Wundt 2.0 and the models of Cohen et al. (1990), Cohen and Huston (1994), and Phaf et al. (1990), or the version of Wundt 2.0 with response inhibition only and the model of Stafford and Gurney (2007), fail to explain the time course data. The models in the literature have inhibitory connections in the subordinate processing network that links stimuli to responses, but attentional control does not involve top-down inhibition of irrelevant perceptions or responses. Instead, the activation of appropriate nodes is selectively enhanced rather than the activation of inappropriate nodes being selectively inhibited. The present computer simulations demonstrate that only the versions of Wundt’s model that include perceptual inhibition explain the time course data on Stroop test performance.

The final statement of Wundt on apperception was that its influence is inhibitory (e.g., Wundt, 1902). This assumption of inhibition is not part of several models (i.e., Cohen et al., 1990; Cohen & Huston, 1994; Phaf et al., 1990), but it is often made for the Stroop test. For example, Gazzaniga et al. (2002) stated that
“the subject must name the color of the words, inhibiting the natural tendency to read the word names themselves” (p. 534). Wundt argued that inhibition may be optionally applied to perceptions, responses, or both. There is converging empirical evidence for the inhibition of irrelevant perceptions but not for inhibition of irrelevant responses in the Stroop test, as I outline next.

Perceptual Inhibition

Much evidence indicates that top-down perceptual inhibition is reflected in the amplitude of oscillatory brain activity in the alpha frequency band (e.g., Bengson et al., 2020; Jensen & Mazaheri, 2010; Klimesch, 2012; Mathewson et al., 2011; but see Foster & Awh, 2019). Many studies show that alpha power increases over brain regions reflecting task-irrelevant processing, indicating inhibition of the regions. In Stroop color naming (SOA = 0 ms), alpha activity occurs in the time window 50–250 ms post stimulus onset, which is when perceptual processing takes place (e.g., Indefrey, 2011; Shitova et al., 2016). The activity is observed at occipital and parietal recording sites and travels in anterior direction across the brain (Klimesch et al., 2007). The alpha activity does not differ between the incongruent and congruent distractor conditions, which is expected under inhibition of word perception with random stimulus presentation. In agreement with these empirical data, inhibition was applied regardless of Stroop condition to SC and O nodes shortly after distractor onset.

Alpha activity may differ in the interstimulus interval depending on the Stroop condition of the previous trial, reflecting the Gratton effect (Gratton et al., 1992). This is the finding that the Stroop effect (i.e., incongruent − congruent) in color naming is larger following congruent than following incongruent trials. Replicating the Gratton effect in RTs, Compton et al. (2012) observed that during the interstimulus interval, alpha power is lower following congruent trials than following incongruent and neutral trials, which did not differ. This provides evidence that attentional control is actively adjusted following congruent trials (hence the lower alpha power), such that subsequent distractor perception is inhibited less. As a consequence, the distractor word has a bigger impact during postcongruent than during postincongruent and postneutral trials, as evident in the magnitude of the Stroop effect (see Lamers & Roelofs, 2011).

Figure 9 shows the results of simulations of the Gratton effect with the version of Wundt 2.0 that assumed perceptual inhibition and an architectural difference (#6). The attentional control adjustment following a congruent trial consisted of a reduction of perceptual inhibition from 0.05 to 0.10 (i.e., from −95% to −90%). In the Compton et al. (2012) study, the participants had to press color-coded buttons to indicate the response. Given that the model
of Wundt has no representations of manual button-press responses, I assumed vocal responding in the simulations of the Gratton effect, as in the earlier time course simulations. Lamers and Roelofs (2011) observed that the Gratton effect in Stroop color naming (i.e., the empirical pattern in Figure 9) is the same for manual and vocal responses. The simulation outcomes demonstrate that adjustment of perceptual inhibition captures the empirical findings on the Gratton effect.

The behavioral Gratton effect can be explained not only by model version #6 but also by the other versions. However, the findings on alpha oscillations only agree with the model versions that include perceptual inhibition (i.e., #3–#6). Later, I argue that

**Figure 8**
Effect of Changing the Value of the Apperception Strength Parameter in Each Version of Wundt 2.0

**Figure 9**
Empirically Observed and Simulated Stroop Effects (Incongruent – Congruent) as a Function of Previous Trial Type

*Note.* lat = apperception latency.

Note. lat = apperception latency; str = apperception strength; MAE = mean absolute error.
model version #6 does best in light of other evidence, and therefore only the RT pattern for this version is shown here.

Wundt 2.0 may treat effects of experiment-wide contingencies in the same way as the previous-trial-type effect (see also Gratton et al., 1992). If the proportion of congruent trials in an experiment is high (e.g., 80%), a lower strength of top-down control may suffice for most of the trials. However, a reduced strength of top-down control will increase RT on the incongruent trials, and as a consequence, the magnitude of the Stroop effect increases. Moreover, with an overall high proportion of congruent trials, it will be difficult to maintain the goal of naming the color and not to read the word, especially for participants with low working memory capacity, increasing error rate (Kane & Engle, 2003).

Inhibition of Responses

Evidence indicates that response inhibition is underpinned by a specific neural circuitry in the brain, consisting of the pre-SMA, subthalamic nucleus, and right inferior frontal gyrus (for a review, e.g., Jahfari et al., 2011). This circuitry is active in the stop-signal task, where responses unexpectedly need to be inhibited on some trials indicated by a cue (e.g., Aron et al., 2007). Moreover, the circuitry is active in the Simon task (e.g., Forstmann et al., 2008). In this task, participants see stimuli, for example a red or green color rectangle, on the left or right side of a computer screen, and they have to indicate the identity of the color by pressing a color-labeled left or right button. RT is longer, and the inhibition circuitry is activated more, on trials in which stimulus and response are on opposite sides than when they are on the same side. However, meta-analyses of studies do not show activation of this circuitry in Stroop color naming (Laird et al., 2005; Nee et al., 2007; Neumann et al., 2005), indicating the absence of response inhibition in this task. Furthermore, Khng and Lee (2014) observed that Stroop scores and stop-signal measures of inhibition are not correlated. It should be noted, however, that the reliability of difference-score metrics is particularly poor, which may impede the observation of this particular correlation based on difference scores (Hedge et al., 2018). Using a combined-task instead of a correlation approach, shared interference between the stop-signal task and the Simon task has been observed (e.g., Verbruggen et al., 2004). Moreover, the two tasks load on a common factor in structural equation modeling (e.g., Friedman et al., 2008; Miyake et al., 2000). However, Verbruggen et al. stated that their “results suggest that a certain overlap exists” (p. 34) but that this does not have to be response inhibition. Moreover, Friedman et al. assumed that the common factor concerns “the active maintenance and management of the current task goals” (p. 219). Thus, the evidence from combined-task and structural equation modeling studies does not necessarily imply that the Simon task engages response inhibition, even when the stop-signal condition does. Logan et al. (2015) advanced a model for stop-signal task performance that assumes that a response is stopped by blocking its input rather than by inhibiting the growth of its activation (similar to Wundt’s assumption that response inhibition concerns the input to L nodes).

Response inhibition may also be assessed by examining RT distributions. In general, interference from distractors should increase monotonically with RT (see Luce, 1986), but response inhibition may counteract this trend by reducing distractor effects, such that interference is smaller for slow responses (e.g., Ridderinkhof, 2002). Delta plots display condition differences as a function of RT quantile, and may be constructed to examine whether differences become smaller, or even reverse, in the slow right tail of a distribution. If response inhibition is present, the slope of the delta plot may become negative for the slowest responses. This decrease of interference for the slowest responses has repeatedly been observed for Eriksen and Simon task performance (for reviews, see Pratte et al., 2010; Proctor et al., 2011; Van den Wildenberg et al., 2010). In the Eriksen flanker task, participants see a target letter, for example an H, surrounded by distractor letters on each side, which may be congruent (i.e., H) or incongruent (e.g., S). They have to indicate the identity of the central letter by pressing a letter-labeled button. RT is longer on incongruent than on congruent trials, but this difference does not steadily increase with increasing RT but may level off for the slowest responses (Ridderinkhof et al., 2005). This points to the presence of response inhibition in the Eriksen flanker task. In the Simon task, interference steadily decreases with increasing RT (Pratte et al., 2010). Moreover, in a neuroimaging study, Forstmann et al. (2008) observed that activity in one part of the response inhibition circuitry, right inferior frontal gyrus, correlated with the slope of the delta plot for the slowest responses in the Simon task. Interference decreased with increasing RT. In contrast, in Stroop color naming, interference increases with increasing RT (for a review, see Pratte et al., 2010), suggesting the absence of response inhibition in this task. It should be noted, however, that the evidence on delta plots in Stroop task performance reviewed by Pratte et al. came from adults responding manually or from children. Although Elliott et al. (2014) observed the same pattern for adults responding vocally, it remains important to replicate the increase of interference with increasing RT for the classic Stroop situation with vocal responding.

The increase of interference with increasing RT that is typical for the Simon task, however, is not a necessary pattern. Using manual responding, Sharma et al. (2010) observed the increasing pattern when participants performed the Stroop color naming task alone, but interference leveled off with increasing RT when a confederate sat next to the participant. This suggests that response inhibition in (manual) Stroop color naming may be engaged under social pressure (which is normally absent in a Stroop experiment). The finding implies that inhibition may optionally be applied to the response level, in line with Wundt’s (1902) model.

Studies show that during the time window of response selection, theta oscillatory power over medial frontal cortex increases with increasing Stroop interference (Hanslmayr et al., 2008). The same is observed for picture-word interference (Piai et al., 2014). The theta activity appears to reflect the resolution of response competition (see Nigbur et al., 2012). Cavanagh and Frank (2014) argued that, more generally, frontal theta reflects a common mechanism for implementing adaptive control in a variety of contexts involving uncertainty about actions and outcomes. Computer simulations of picture-word interference with WEAVER++ by Piai et al. support the view that theta reflects enhancement of the correct response in this task (see Roelofs, 2003; Roelofs & Hagoort, 2002; Roelofs et al., 2006). Thus, this model assumes both blocking of irrelevant perceptions and enhancement of responses, which appear to be reflected in alpha and theta oscillatory activity, respectively. Wundt did not envision such a mixture of top-down mechanisms (see Footnote 8 above) but assumed either enhancement
(e.g., Wundt, 1880) or inhibition (Wundt, 1902). In picture-word interference, the Gratton effect in the time window of response selection is reflected in theta power over medial frontal cortex (Shitova et al., 2017).

To conclude, converging evidence indicates that inhibition in Stroop color naming involves the perception of the distractor but normally not the response to the distractor. The perceptual inhibition versions of the model of Wundt agree with this evidence.

### Automaticity of Reading

Another assumption that is often made about the Stroop effect is that it reflects the automaticity of reading, following Cattell (1886). For example, Gazzaniga et al. (2002) stated that "activation of a representation based on the words rather than the colors of the words appears to be automatic . . . skilled readers have years of practice" (p. 102). However, evidence against this assumption has been available for a long time and is still accumulating.

One piece of evidence against automaticity of reading as the cause of Stroop interference in color naming comes from age groups. Comalli et al. (1962) used the card-version of the Stroop test to examine color naming and word reading in different age groups. Participants ages seven to 13 years were drawn from a grammar school, ages 17–19 were undergraduate students, ages 25–44 were drawn from an evening college, and ages 65–80 were drawn from a community club. If Stroop interference in color naming is attributable to the automaticity of reading, the interference should increase as reading becomes more automatic. However, Comalli et al. observed that while reading RT decreased from ages seven to 17–19 years (suggesting greater automaticity), Stroop interference in color naming also decreased. In fact, color naming RT also decreased (the lines for reading and naming were parallel), in line with Brown (1915). From ages 17–19 to 65–80 years, the naming and reading RTs did not change, but Stroop interference increased between ages 35–44 and 65–80 years. These results indicate that Stroop interference is not caused by automaticity of reading. Instead, the findings are better explained by assuming that attentional control improves between ages seven to 17–19 years, reducing the interference, and later worsens again between ages 35–44 and 65–80 years, increasing the interference. Thus, my argument here is that increased practice on word reading leads to better top-down control of this task (as reflected in the decreased Stroop interference), and that in older age, top-down control diminishes again (as reflected in the increased Stroop interference).

### Architectural Difference

The Stroop asymmetry indicates that in processing color-word combinations, the reading response is more prepotent than the color naming response. Assuming a difference in strength (Cattell, 1886) is not the only way to explain this difference in prepotency, but an alternative explanation is that the functional architecture differs between color naming and word reading (Brown, 1915). Models of word reading (e.g., Coltheart et al., 2001; Dehaene, 2009; Pritchard et al., 2018; Seidenberg & McClelland, 1989) assume that words may be read aloud through at least two routes, one directly linking input letters to output sounds and the other indirectly linking input letters via lexical or meaning nodes to output sounds. That two reading routes exist is shown by brain damage in acquired dyslexia, which may cause either the direct or the indirect route to be no longer available for reading. Normally, words can be read aloud without engaging meaning. In contrast, color and picture naming necessarily involve meaning. As a consequence of this architectural difference, reading aloud is not affected by incongruent colors, whereas color naming is hampered by incongruent words. In Roelofs (2003), I showed the utility of this architectural assumption in accounting for the Stroop asymmetry.

### Conclusion

Given the converging evidence against response inhibition in the Stroop test, and against reading automaticity as the cause of the interference, version #6 of Wundt’s model provides the best explanation of the time course data. This model version assumes apperceptive inhibition of distractor perception and a reading shortcut rather than greater automaticity. This agrees with my conclusion in Roelofs (2003), based on simulations with the WEAVER model, that an account of the Stroop effect and its time course requires the assumptions of distractor blocking and an architectural difference between naming and reading.

### Other Implemented Models

As indicated earlier, other implemented models of Stroop task performance (i.e., Melara & Algom, 2003; Kalanthroff et al., 2018) have not been applied to the time course data or they also capture the findings (Chuderski & Smolen, 2016). The model of Melara and Algom assumes top-down inhibition of the irrelevant perceptual dimension and therefore is likely able to explain the time course of interference observed by Glaser and Glaser (1982) and others. However, naming and reading are assumed to differ in automaticity, owing to a presumed greater amount of practice of reading. This assumption of the model is challenged by the find-
ings reviewed above. The model of Kalanthroff et al. also assumes a difference in automaticity between naming and reading, and moreover, assumes top-down enhancement of color perception in color naming. This makes it unlikely that the model can explain the time course of Stroop interference. Nevertheless, for both models, it is important to conduct computer simulations to assess whether these conclusions regarding the time course of interference in the models are correct. Chuderski and Smolen explained the Stroop effect in terms of utility-based condition-action rule selection, whereby top-down control decreases the utility of the word-reading rule in color naming. This is functionally equivalent to inhibition. Computer simulations revealed that their model accounts for the SOA curves of interference in color naming obtained by Glaser and Glaser. Although the model exhibits the Stroop asymmetry, some interference of incongruent colors in word reading is present at zero SOA, however. The Stroop asymmetry in the model reflects the assumption that the base utility is much higher for reading than for color naming, reflecting presumed greater automaticity of reading. As we saw, this assumption is challenged by the empirical evidence.

**Picture-Word Interference Task**

The patterns of SOA results obtained with the color-word Stroop task are also observed in the picture-word analog, in which participants name pictured objects (e.g., a picture of a cat; say “cat”) while trying to ignore superimposed printed distractor words, which may be incongruent (e.g., dog) or congruent (cat), or they see a row of Xs in the neutral condition (e.g., Damian & Martin, 1999; Glaser & Düngelhoff, 1984; Rayner & Springer, 1986; Starreveld & La Heij, 1996). Figure 10 displays the classic data obtained by Glaser and Düngelhoff and the results of simulations with version #6 of Wundt 2.0. The figure shows that the model generally captures the data patterns.

Evidence suggests that response inhibition may be used to suppress incorrect picture names that are coactivated during lexical response selection in simple picture naming (Shao et al., 2012, 2014), even though response inhibition is not employed in Stroop color naming. Shao et al. (2015) had participants perform color-word Stroop and picture-word interference tasks, and examined Stroop interference (i.e., incongruent — neutral) and semantic interference (i.e., semantically related — unrelated) by performing delta plot analyses. The slopes of the interference effects for the longest naming RTs correlated with the magnitude of the mean interference effect in the picture-word interference task but not in the Stroop task. The results suggest that participants used response inhibition to reduce semantic interference but not Stroop interference. Again, this demonstrates that response inhibition may be optionally applied, depending on the task.

The utility of response inhibition is different for the Simon, Eriksen flanker, color-word Stroop, and picture-word interference tasks. In the Simon task, the stimulus identity (e.g., a red or green rectangle) and location (i.e., left or right side of the computer screen) are processed through different perceptual channels (i.e., ventral and dorsal streams in the brain, see Gazzaniga et al., 2002). However, location processing cannot be inhibited because it is needed for locating the stimulus on the screen. Therefore, response inhibition is used to reduce interference, as evident from delta plots. In the Eriksen task, target and flanker letters differ in spatial location. Spatial attention may be used for separating target and flankers, and interference is reduced by response inhibition, as reflected in delta plots. In color-word Stroop and picture-word interference, perceptual channels differ for target and distractor (i.e., different regions in occipital-temporal cortex, see Dehaene, 2009), and inhibition of word perception reduces interference. Pictures are informationally much richer than colors. For example, a picture of a cat also shows ears, whiskers, a tail, and so forth. Thus, pictures, but not colors, habitually activate several competing names and response inhibition may reduce the lexical competition induced by pictures. I hypothesize that in picture-word interference, the response inhibition that is routinely triggered by pictures is also used to reduce distractor interference. This would explain why response inhibition is engaged in picture-word interference but not (or less commonly) in color-word Stroop.

In an EEG study of simple picture naming, Jongman et al. (2020) observed that prestimulus alpha power over motor cortex predicts picture naming RTs. This suggests that inhibition of the articulatory system before picture onset reduces interference from premature motor activation during picture name planning. In terms of Wundt’s model, apperceptive inhibition is applied to MC nodes before picture onset.

**Testing the Relation Between Attention and g**

Earlier, I indicated that Wundt distinguished between simple and complex apperceptive functions. The simple apperceptive
functions of relating and comparing played a central role in the simulations of Stroop task performance, as did apperceptive inhibition. The complex apperceptive functions of synthesizing and analyzing are assumed to be involved in more intellectual tasks, in addition to the simple functions. According to Wundt (1896/1897), the ability here concerns “the perception of agreements and differences and other derived logical relations between contents of experience” (p. 263). Carpenter et al. (1990) showed that the ability to analyze stimuli for correspondences and differences and to induce abstract relations is central to the Raven Progressive Matrices test (e.g., Raven et al., 1998). Each problem in the Raven test consists of a 3 × 3 visual matrix with the bottom right cell missing. Each of the other cells contains one to five visual elements, such as geometric figures, textured lines, and line orientations. The task is to look across the rows and columns to determine the regularities and then to select the missing cell from among eight alternatives given below the matrix. In Wundt’s terms, this involves apperceptive relating and comparing, and inhibiting of irrelevant information, to determine the regularities through apperceptive analysis and synthesis. The Raven test provides a good estimate of Spearman’s (1904) general intelligence factor (e.g., Carpenter et al., 1990).

Spearman (1904) observed that correlations among scores of numerous individuals on a wide range of cognitive tasks (e.g., mathematics, language, music, perceptual discrimination) are all strong positive. On the basis of this observation, he argued for the existence of a general intelligence factor, which he called g. To the extent that cognitive tasks draw on g, strong positive correlations should be observed between task scores. Wundt (1911) argued that g reflects an individual’s general apperception ability. He stated:

Spearman concludes from his results that the central factor, which determines all individual correlations, cannot be attributed to any psychological force, especially not to the tension of attention. . . . I find it hard to believe that these reasons are sufficient to reject the interpretation that attentional performance is the central factor.10 (1911, p. 598, my translation)

Spearman (1927) rejected Wundt’s claim. However, a link between attentional control and general intelligence is supported by an overlap in brain activations by tasks tapping into attention or intelligence, in particular, in prefrontal and parietal cortex (e.g., Duncan, 2010). Barbay et al. (2012) observed that damage to these common areas reduces both general intelligence and attentional control ability. Moreover, behavioral measures of attentional control and g are correlated, although the correlation is not perfect. In a structural equation modeling study, Friedman et al. (2008) observed that the correlation between a WAIS-IQ estimate of general intelligence and attentional control (they used the term executive control) is .57 at the level of latent variables. The nonperfect correlation indicates that it is not the case that attentional control is the g factor, as Wundt maintained, but attentional control may contribute to g. Evidence suggests that the correlation between attentional control and intelligence is not mediated by the inhibition ability but by the ability to update working memory (Friedman et al., 2006). However, as latent variables, updating and inhibition are correlated, and inhibition appears to be engaged to some extent by any task requiring executive control (Friedman et al., 2008; Miyake & Friedman, 2012). Moreover, measures of resting-state alpha band activity are correlated with measures of intelligence (e.g., Doppelmayr et al., 2002, 2005), including scores on the Raven test (Zakharov et al., 2020). Knowlton et al. (2012) presented a neurocomputational model that assumes a key role for top-down inhibition of task-irrelevant information in relational reasoning. Atchley et al. (2017) observed that error responses in (manual) Stroop task performance are preceded by a decrease in alpha band activity, suggesting that errors occur when the perception of the distractor word is insufficiently inhibited.

Duncan (2010) argued that g relates to task performance through goal neglect, defined as the ignoring of task demands even if they have been understood. Duncan et al. (2008) observed that high-g individuals experience less goal neglect than low-g individuals. Kane and Engle (2002) related goal neglect to the ability to maintain stimulus representations and goals in working memory (WM), especially when facing distraction. WM is assumed to consist of short-term memory (STM) and attentional control (referred to as “executive attention”), which is the mechanism that links WM capacity with higher cognitive abilities, including general intelligence. Individual differences in WM capacity and intelligence are positively correlated. In discussing errors in Stroop task performance, Kane and Engle stated that:

This view is supported by research examining the relation between WM capacity and goal neglect in the Stroop task (Kane & Engle, 2003; Meier & Kane, 2013; Morey et al., 2012).

In previous research, a negative correlation between g and the magnitude of the Stroop effect has been observed (for a review, see Kane & Engle, 2002). As concerns goal neglect, errors occur in Wundt’s (1902) model if an L node is selected before the relating processes has been completed (otherwise correctly determining the response), resulting in fast but incorrect responses. This predicts a negative correlation between g and the Stroop effect in fast errors, which has not been tested before. One aim of the study reported below was to test whether individual differences in g predict, to some extent, individual differences in the magnitude of the Stroop effect in color naming, particularly in fast errors. First, I used the Raven test to estimate the magnitude of g for each participant. Next, the participants performed the Stroop color naming task with congruent, incongruent, and neutral stimuli. Speed and accuracy of color naming were measured. If attentional control contributes to Spearman’s g, then a higher g predicts a smaller Stroop effect in RT or percent error (PE), and negative correlations should be found, especially for fast
error responses. Another aim of the study was to conduct delta plot analyses to examine whether the Stroop effect in RT increases with increasing RT, which would replicate previous evidence against response inhibition and support Wundt’s model version #6. Pratte et al. (2010) reviewed evidence from adults responding manually and from children, which indicated that Stroop interference increases with increasing RT. The present study tests whether this also holds for adults responding vocally, which would replicate Elliott et al. (2014).

Method

Participants

Power analysis using G*Power (Faul et al., 2009) revealed that to detect a correlation of $-0.50$ (see Friedman et al., 2008) with a power of 0.95 in a one-tailed test, the study would need 34 participants. The correlation of Friedman et al. concerned a factor loading, for which the power calculation is not the same as for a correlation between two single tasks. Kane and Engle (2002) referred to a poster by Kane et al. reporting that a single general-intelligence measure correlated with Stroop interference at $r = -0.49$.

The present study was carried out with 38 paid participants (28 women, mean age 23 years, range 18–43 years), who were students at Radboud University, Nijmegen. All were young adults and native speakers of Dutch. They participated in the experiment for monetary compensation or course credits. All had corrected-to-normal vision and gave written consent. The study was approved by the Ethics Committee for Behavioural Research of the Social Sciences Faculty at Radboud University, Nijmegen.

Materials and Design

The booklet of the Standard Progressive Matrices (Raven et al., 1998) contains 60 items listed in order of difficulty. Each item consists of a matrix with eight patterns for which the participant is asked to select the correct one. The stimuli for Stroop color naming consisted of the written Dutch color words rood, groen, and blauw in one of the three ink colors red, green, or blue. The written words were presented in 36-point lower-case Arial font. A row of five Xs served as stimulus in the neutral condition. On average, the words and Xs subtended 2.3° vertically and 6.3° horizontally at a viewing distance of 50 cm. There were three congruent pairings of the word and color, three incongruent pairings (rood–blue, groen–red, blauw–green), and three neutral stimuli (the row of Xs in an ink color). Each of the congruent, incongruent, and neutral stimuli occurred 39 times, thus there were 117 trials per condition. The stimuli were presented in random order.

Procedure and Apparatus

The participants were given 20 min to work on the Raven test. Previous research has shown that this short duration for the test is enough to obtain a good estimate of $g$ (Hamel & Schmittmann, 2006).

The Stroop experiment was run using Presentation software. The participants were tested individually. They were seated in front of a computer monitor and a microphone connected to an electronic voice key. The distance between participant and screen was approximately 50 cm. The participants were asked to name the ink color as quickly as possible while trying to make no mistakes.

A trial started with the presentation of the Stroop stimulus, which always remained visible for 1.5 s. Following stimulus presentation, the screen was blank for 2 s. The voice key recorded the RT completely separately from the visual stimulus. After the blank period, the next trial began. A desktop computer controlled the stimulus presentation and data collection, including the voice key.

Analyses

For the Raven test, the number of correct responses was counted for each participant. In the Stroop test, trials were classified as incorrect if they included a wrong response word or a nonfluency (e.g., disruption or partial repetition). Incorrect trials were excluded from the statistical analyses of the RTs. The RTs and PEs were submitted to repeated measures analyses of variance with RT and PE as dependent variables and Stroop condition as the independent variable.

Stroop scores were computed as the difference in RT or PE between incongruent and congruent trials or between incongruent and neutral trials. Pearson correlations were computed to quantify the correlation between Raven and Stroop scores. To quantify the strength of the statistical evidence for a negative correlation, I performed Bayesian statistical analyses and report Bayes factors (e.g., Wagenmakers et al., 2018). A Bayes factor quantifies the evidence that the data provide for one hypothesis versus another. For example, when the Bayes factor $BF_{10}$ equals 10, the data are 10 times more likely under $H_1$ than under $H_0$. The Bayesian analyses were done using JASP (Love et al., 2019). The analyses used JASP’s Cauchy priors with default parameter settings (for a defense, see Wagenmakers et al.). Under a standard interpretation, a $BF_{10}$ of 3–10 indicates “moderate evidence,” 10–30 “strong evidence,” 30–100 “very strong evidence,” and >100 “extreme evidence” for $H_1$. Below, $BF_{10}$ indicates that $H_1$ specifies that measure 1 > measure 2, and $BF_{01}$ indicates that the alternative hypothesis specifies that the correlation is negative.

In addition to analyses of mean performance, distributional analyses of RT and accuracy were conducted. To obtain Vincen-tized RT distributions (Ratcliff, 1979), the RTs for each participant and Stroop condition were rank ordered and divided into five RT quantiles (20% bins) of equal or near-equal size. Next, the mean RT was determined for each quintile in each condition. Vincen-tizing is a way to represent the RT distribution of a group while preserving the shape of the individual distributions (see also Woodworth, 1938; Woodworth & Schlosberg, 1954). The delta plot for the Stroop effect was obtained by computing, for each quintile, the RT difference between the incongruent and congruent conditions (Riddervold, 2002). Conditional accuracy functions plot accuracy of responding as a function of response speed. These were obtained by rank ordering the RTs of both correct and incorrect trials and dividing them into five RT quantiles (20% bins) of equal or near-equal size. Next, the mean accuracy ($1 - PE$) was determined for each quintile in each condition (Riddervold, 2002).

The data of the study are available from the archive of the open science framework (Roelofs, 2020).
Results and Discussion

The mean Raven score was 21.55 with a standard deviation of 4.54 and a range of 12.00–33.00. Table 3 gives the mean color naming RT and PE for the distractor conditions. Nearly all errors involved producing a wrong word, either completely (e.g., saying “green” instead of “red” in response to the word “green” in red color) or partially (e.g., saying “gree-red” for the intended response “red”). Sometimes a nonfluency occurred (e.g., saying “re-uh-red” on a congruent trial, suggesting premature responding). RT was longer and PE was higher in the incongruent than in the congruent and the neutral conditions, which did not differ much. The Bayesian statistical analyses showed that relative to the null model, there was decisive evidence for a main effect of Stroop condition in RT ($BF_{10} = 1.36e+25$) and PE ($BF_{10} = 9.61e+10$). Pairwise comparisons revealed that RT was longer in the incongruent than in the neutral ($BF_{10} = 9.44e+14$) and congruent ($BF_{10} = 1.69e+13$) conditions, which did not differ ($BF_{10} = 0.13$). Also, PE was higher in the incongruent than in the neutral ($BF_{10} = 39,700$) and congruent ($BF_{10} = 358,226$) conditions, which did not really differ ($BF_{10} = 2.82$). Thus, the experiment replicates the standard findings on Stroop color naming.

Table 4 gives the Pearson correlations between Raven and Stroop scores for RT and PE, and corresponding 95% confidence intervals, $p$ values, and Bayes factors. The table shows that there is moderate to strong evidence for a negative correlation for PE and an absence of a correlation for RT.

The observation that an individual’s $g$ predicts, to some extent, the magnitude of the individual’s Stroop effect is in agreement with Wundt’s (1911) suggestion that $g$ reflects an individual’s ability of attentional control. Moreover, the observation that $g$ predicts the Stroop effect in PE but not in RT agrees with Duncan’s (2010) suggestion that $g$ relates to task performance through goal neglect, with high-$g$ individuals suffering less from goal neglect than low-$g$ individuals.

Figure 11 shows the Vincentized cumulative distribution curves for RT in the incongruent, neutral, and congruent distractor conditions (left panel) and accuracy (i.e., $1.0 - PE$) per condition plotted as a function of RT quintile (right panel). The inset shows delta RT (incongruent $-$ congruent) as a function of RT quintile with a linear trendline, with $R^2 = .995$. The RT quintile values on the horizontal axis are the means of the corresponding condition RTs (see Ridderinkhof, 2002). Bayesian analyses showed that there is very strong evidence that all four slopes of the delta plot are positive (all $BF_{10} > 30$), different from what is typically observed for the Simon and Eriksen tasks (see Pratte et al., 2010). The observed increase of the magnitude of the Stroop effect with $g$ agrees with prior evidence on Stroop color naming. The observed increase of the magnitude of the Stroop effect with $g$ replicates the standard findings on Stroop color naming.

In the Grundzüge, Wundt discussed several varieties of attention, such as sustaining attention over time, the orienting of attention through overt eye movements or covert shifts, and the top-down regulation of mental processes. For example, Wundt (1911) discussed fluctuations of attention over time ("Schwankungen der Aufmerksamkeit," pp. 345–352). Moreover, Wundt (1910) addressed the orienting of attention ("Orienterung"), assuming that as a rule, there is a correspondence between attention and eye fixation ("Gesetz der Korrespondenz von Apperzeption und Fixation"), although it is possible to shift attention while maintaining eye fixation (pp. 560–565). Finally, Wundt (1908) discussed attentional control (pp. 378–385), including top-down inhibition, which is the topic of the present article. Numerous modern studies, including neuropsychological examinations, have shown that these different varieties of attention are underpinned by separable attentional abilities, listed in Figure 12. Wundt’s seminal observations, however, appear to be unknown to many authors. As Fahrenberg (2019) put it: “Neuropsychology appears to have begun during the 1960s in the US for these authors, with the exception of the old problem of attention, for which they refer to William James (1890), but not to Wundt” (p. 47).

According to an influential theory of Posner and colleagues (Posner & Raichle, 1994; Posner, 2012, for a review), attention consists of alerting, orienting, and executive control abilities. Alerting is the ability to achieve and maintain alertness, either briefly or sustained over a prolonged period of time. Orienting is the ability to shift the locus of perceptual processing toward a particular location, either with or without corresponding eye move-

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11 Frequentist statistical analyses yielded a main effect of Stroop condition in RT, $F(2, 74) = 175.0, \ p < .001, \ \eta^2 = 0.83,$ and PE, $F(2, 74) = 37.98, \ p < .001, \ \eta^2 = 0.51$. Pairwise comparisons (Bonferroni corrected, i.e., the $p$ values were adjusted for comparing a family of three) revealed that RT differed between the incongruent and the neutral ($t = 15.40, \ p < .001, \ d = 2.50$) and congruent ($t = 13.49, \ p < .001, \ d = 2.19$) conditions, which did not differ ($t = 0.49, \ p > .05, \ d = 0.08$). Also, PE differed between the incongruent and the neutral ($t = 5.90, \ p < .001, \ d = 0.96$) and congruent ($t = 6.66, \ p < .001, \ d = 1.08$) conditions, which did not differ ($t = 2.18, \ p > .11, \ d = 0.35$).
Table 3

Descriptive Statistics on Stroop Color Naming for Reaction Time and Percent Error

| Statistic | Reaction time | | | | Percent error | | |
|-----------|---------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
|           | Congruent     | Incongruent      | Neutral          | Congruent        | Incongruent      | Neutral          |                  |                  |                  |
| M         | 653           | 754              | 651              | 0.45             | 3.87             | 0.79             |                  |                  |                  |
| SD        | 74            | 93               | 76               | 0.86             | 3.17             | 1.02             |                  |                  |                  |
| Upper 95% CI | 677       | 785              | 676              | 0.73             | 4.91             | 1.13             |                  |                  |                  |
| Lower 95% CI | 629       | 723              | 626              | 0.17             | 2.82             | 0.45             |                  |                  |                  |

Note. Reaction time in milliseconds. M = mean; SD = standard deviation; CI = confidence interval.

Table 4

Pearson Correlation (r) Between Raven and Stroop Scores for Reaction Time and Percent Error and Corresponding 95% Confidence Interval, p Value, and Bayes Factor (BF)

<table>
<thead>
<tr>
<th>Effect type</th>
<th>r</th>
<th>95% CI</th>
<th>p</th>
<th>BF_{10}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction time incongruent − congruent</td>
<td>0.10</td>
<td>[−1.0, 0.36]</td>
<td>.72</td>
<td>0.14</td>
</tr>
<tr>
<td>Reaction time incongruent − neutral</td>
<td>0.04</td>
<td>[−1.0, 0.31]</td>
<td>.59</td>
<td>0.17</td>
</tr>
<tr>
<td>Percent error incongruent − congruent</td>
<td>−0.42</td>
<td>[−1.0, −0.16]</td>
<td>.005</td>
<td>10.49</td>
</tr>
<tr>
<td>Percent error incongruent − neutral</td>
<td>−0.38</td>
<td>[−1.0, −0.13]</td>
<td>.009</td>
<td>6.14</td>
</tr>
</tbody>
</table>

Note. For all tests, the alternative hypothesis specifies that the correlation is negative.
number of separate acts of apperception following one another12 (1897, p. 212). Whereas it has long been assumed that individuals look at objects in the visual world just as long as is needed to identify them and that response factors play no role (e.g., Meyer & Kieras, 1997), psycholinguistic research indicates that when individuals name objects, gaze shifts depend on the time to plan their names. For example, when participants are asked to name two objects, one presented on the left side of a computer screen and the other on the right side, gaze shifts to the right occur later for left-side objects with disyllabic names (e.g., camel) than with monosyllabic names (e.g., swan) even when the object recognition times do not differ (Meyer et al., 2003). The effect of the number of syllables suggests that the shift of gaze from one object to the other is initiated only after the phonological form of the name for the object has been encoded.

Similarly, in the color-word Stroop task, individuals shift gaze only after response selection (Roelofs, 2011, 2014b). In eye tracking experiments, participants were presented with color-word Stroop stimuli and left- or right-pointing arrows (surrounded by Xs, i.e., XX > XX or XX < XX) on different sides of a computer screen, as illustrated in Figure 13. They named the color and shifted their gaze to the arrow to manually indicate its direction by a left or right button press. Naming RT, gaze shift latencies, and manual RT were measured. The SOA between color and word was manipulated (Roelofs, 2014b). The results showed that Stroop interference and its characteristic time course (see Figures 2 and 10) is present to the same extent in all three measures, indicating that gaze shifts occur after response selection in color naming. Figure 13 shows the Stroop effect (i.e., incongruent − neutral) in the gaze shift latencies as a function of SOA. In terms of Wundt’s model, apperception in the Stroop task concerns both perceptions (i.e., perceptual inhibition) and responses (i.e., determination of the target response through relating). If gaze shifts are initiated after response selection, the characteristic pattern of Stroop interference should be present in the gaze shifts, as empirically observed.

To summarize, Wundt discussed several varieties of attention, including sustaining attention over time, the orienting of attention through overt eye movements or covert shifts, and the top-down regulation of mental processes. These distinctions foreshadowed modern conceptualizations of attention and control. Moreover, Wundt argued that attentional control is manifest in the products of the human mind, including language, for which he developed a production theory. Predictions from this theory about attention and gaze shifting have been confirmed in modern psycholinguistic research as well as in studies using the Stroop task.

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12 “Demnach ist die successive Bewegung der Aufmerksamkeit über eine Vielzahl psychischer Inhalte stets ein discontinuirlicher Vorgang, der aus einer Mehrzahl auf einander folgender gesonderter Apperceptionsacte besteht” (Wundt, 1896, p. 294).
Generalized Lessons

Wundt was Leipzig’s most popular lecturer. According to Levelt (2013), he filled the largest auditorium of the university, with some 300 students attending: “The tall and slender Wundt, clad in black, would deliver his lecture in ‘an easy and abundant bass, somewhat toneless’ . . . Titchener remembered. Others remembered his chiseled language and well-prepared experimental demonstrations” (p. 167). Wundt’s voice was recorded in 1918 on an analog shellac disk, which has recently been digitally restored (listen to Wundt, 1918b).

As demonstrated in the present article, Wundt also still speaks to us via his work, including his model of how attention controls naming, which appears to teach some important lessons. There are several similarities and differences between Wundt’s model and the implemented models that were published a century later (i.e., Chuderski & Smolen, 2016; Cohen et al., 1990; Cohen & Huston, 1994; Kalanthroff et al., 2018; Melara & Algomo, 2003; Phaf et al., 1990; Roelofs, 2003; Stafford & Gurney, 2007). The successes and failures of the modern models and the different versions of Wundt 2.0 provide evidence for a number of generalized lessons.

First, the simulations with Wundt 2.0 demonstrate that correct performance on the color-word Stroop and picture-word interference tasks requires attentional control. If the naming and reading systems run without top-down regulation, performance fails. This supports the conclusion that control is not an emergent property of associative processing systems (e.g., Eisenreich et al., 2017; Müller, 1913), here the naming and reading systems, but arises from a superordinate system, such as the apperception center of Wundt (1880, 1902), the task nodes of Cohen et al. (1990), and the task symbols in working memory of Roelofs (2003). In the words of Norman and Shallice (1986), an account of attention and performance requires both “horizontal and vertical processing threads” (p. 7).

Second, the simulations with Wundt 2.0 demonstrate that top-down enhancement or response inhibition cannot account for the time course findings on the color-word Stroop and picture-word effects. In these tasks, color naming and picture naming require inhibition of perceptions. Without such inhibition, interference increases with increasing preexposure SOA, contrary to the empirical findings. For the Stroop test, converging empirical evidence indicates that inhibition concerns perceptions but not responses, but this may be different for other tasks (e.g., the Simon and Eriksen flanker tasks). Findings obtained with one task cannot be blindly generalized to other tasks.

Third, the simulations with Wundt 2.0 demonstrate that an account of attention and performance in general, and Stroop test performance in particular, requires assumptions about both top-down control and the controlled subordinate processes (see Kahneman, 1973). To account for the Stroop asymmetry, a difference between color naming and word reading must be assumed, such as a difference in strength or architecture. Converging empirical evidence supports the assumption of a difference in functional architecture between oral naming and reading, which determines the amount of top-down regulation required (see Logan, 2018, for a theory of automaticity and control in typing).

Summary and Conclusion

Wundt was not only the first to examine interference through an SOA manipulation but also advanced the first model of attentional control. According to Wundt (1880, 1902), attentional control (apperception) plays a central role in both simple tasks, like naming an object or reading a word in the context of distractor objects or words, and more complex tasks involving intelligence. I tested a possible computational implementation of Wundt’s model using classic data on the time course of Stroop interference in naming and reading. Eight model versions were examined that assumed attentional control through either enhancement or inhibition, with inhibition applied to both the perceptual and response levels, the perceptual level only, or the response level only, and with color naming differing from reading either in automaticity or functional architecture. Computer simulations demonstrated that the assumption of perceptual inhibition is necessary to account for the time course of the Stroop effect in naming and reading, and together with the assumption of an architectural difference does best in light of other evidence. This corroborates my conclusion in Roelofs (2003) based on simulations with another model, WEAVER++, that an account of the Stroop effect and its time course requires the assumptions of blocking of distractor perception and an architectural difference between naming and reading. Moreover, I tested whether individual differences in performance...
on a more complex task involving intelligence, the Raven test, predict to some extent the magnitude of the Stroop effect, especially in fast errors, which was confirmed. The behavioral evidence on the Stroop and Raven tests agrees with the evidence on oscillatory brain activity in the alpha frequency band associated with both tests.

In the year of his death, 1920, Wundt published his memoirs Erlebtes und Erkanntes (Experienced and known) and the tenth and last volume of his Völkerpsychologie. He had accomplished what he set out to achieve half a century earlier (see the foreword to Wundt, 1874): to help make psychology a science. Blumenthal (2001) stated:

As the darkness closed in on Wundt’s last days . . . the optimism of Wundt’s once gilded age shines in the last utterances of his memoirs (Wundt, 1920) and the last pages of his Völkerpsychologie. He proclaims a faith in the positive, creative, and moral powers of the human mind that he saw leading inevitably to a better future. (p. 142)

However, there turned out to be no such bright future for his own work, which was “soon cast the icon of a dead and failed past” (Blumenthal, 2001, p. 142). Undeservedly so, as I have demonstrated in the present article. Wundt’s model of how attention controls naming has stood the test of time (pun intended) and provides a number of enduring lessons for our understanding of attention and performance.

**Context of Research**

How attention controls naming has been a central question of my research group for almost 15 years. In addressing this question, we have adopted a multimethod approach including measurement of response time and accuracy, eye tracking, electrophysiological and hemodynamic neuroimaging, brain stimulation, tractography, imaging genetics, and computational modeling. As much as possible, our research has been driven by, and aimed to further develop, the WEAVE++ computational model of attention and language performance and its neurocognitive extension WEAVE++/ARC that synthesizes behavioral psycholinguistic, functional neuroimaging, tractography, and aphasiological evidence. Our basic science is linked to application, including the diagnosis and treatment of language deficits after brain damage, an area where attentional control is important. In our publications, we often referred to, and took inspiration from, the work of Wundt, a pioneer of experimental psychology and modern psycholinguistics, who emphasized the importance of the attentional control functions of the frontal lobes.

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