A role for information theory in personality modeling, assessment, and judgment

David M. Condon¹

Department of Psychology
University of Oregon
Eugene, Oregon, USA

René Mõttus²

Department of Psychology
University of Edinburgh
Edinburgh, UK

Institute of Psychology
University of Tartu
Tartu, Estonia

Author Notes: The authors would like to thank Colin DeYoung, William Revelle, and Dustin Wood for their feedback during various stages of this work. Correspondence should be addressed to David M. Condon at dcondon@uoregon.edu.

Abstract

Claude Shannon's groundbreaking work on information theory (Shannon, 1948a) was published just as the field of psychological testing was reaching its potential. Many of the fundamental underpinnings of psychological testing theory were proposed in this same era and the application of these ideas over the ensuing decades has greatly informed our understanding across numerous psychological domains, including individual differences in personality, cognitive abilities, interests, and much more. While the prospect of integrating information theory into psychological assessment was initially received with great enthusiasm, it was quickly and definitively dismissed by Lee Cronbach (1955a), mainly on the grounds that it was incompatible with the practical demands of psychological testing (e.g., limited testing time, relatively small samples). In this chapter, we reconsider Cronbach's rationale in light of recent technological advancements brought about by the "information age," and propose that re-introducing information-theoretic approaches to psychological assessment can advance our knowledge of personality, person-perception, and personality assessment. We conclude by providing several examples of research applications that have already invoked an information theory approach to assessment.

Keywords: Personality, assessment, personality judgment, information theory

Word count: 9,800

INFORMATION THEORY IN PERSONALITY

The field of information theory wrestles with the question of how to convey signal efficiently – quickly and without much loss – from a source to a target. We begin with the assertion that the fundamental goal of personality assessment is to address this same question: to capture and convey the essential psychological individual differences. In this work, we discuss this similarity in detail, arguing that the two fields are linked by more than a superficial analogy, even though the technical details of each discipline seem to have little in common. These ideas are developed through consideration of the briefly overlapping histories of the two fields and the subsequently divergent ways that each has proceeded to address this same challenge. With examples, we advocate for the broader adoption of more information-theoretic approaches in personality assessment as a means of advancing basic personality research.

Importantly, we emphasize from the outset that this work aims to open a line of inquiry that can and hopefully will be continued through more extensive, specific, and empirical evaluation. It does not aim to thoroughly map the more technical aspects of probability theory and statistics used in information theory into personality assessment, largely because the basic precepts of information theory are unfamiliar to those who focus on measuring and modeling persons and situations. It is intended as a high-level overview of the most relevant topics.

Background on Shannon's Information Theory

Our references to information theory in this chapter are rooted in the two-part article by Claude E. Shannon (1948a, 1948b) titled “A Mathematical Theory of Communication.” Setting forth the conceptual basis for modern telecommunication systems, including both the system as a whole and its component parts, this landmark work has become one of the most highly cited papers published to date and is often credited with ushering in the information age. The essence of the article is encapsulated by Shannon's primary observation that:

“The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.” (p. 379, Shannon, 1948a)

This simple statement was a departure from prior work in communications at the time and its novelty stemmed from the call to focus on the *transmission* of messages rather than their nature (e.g., lists of numbers, letters, words, still or moving images). Shannon disregarded the fact that messages “refer to or are correlated according to some system with certain physical or conceptual entities” (Shannon, 1948a, p. 379). He proposed instead that each message can be abstractly represented with a small number of symbols (0s and 1s) as one of a finite set of possible messages (given any fixed length), and in so doing, underscored the utility of focusing on the elemental properties of the messages rather than their interpreted “semantic” meaning. In communications theory, later labeled more broadly as information theory (IT), this utility stemmed from consideration of the underlying units of the messages and message length (i.e., the quantity of information conveyed) rather than more intractable concerns about differential methods for encoding and decoding different *types* of content (i.e., theories of abstraction). As Shannon states, the “semantic aspects of communication are irrelevant to the engineering problem” (p. 380, Shannon, 1948a). At the lowest level, one approach to the communication of messages could suit all types. Drawing a parallel with psychological assessment, this would mean defocusing from the structure of the hypothetical phenomena (e.g., traits) being assessed and prioritizing the efficacy of obtaining information about how individuals vary (Condon et al., 2020).

INFORMATION THEORY IN PERSONALITY

Shannon built on this essential idea by identifying several properties of the low-level representations of the content to be conveyed and the process of conveyance itself — the communication system. Here, we primarily focus on the latter (the conveyance of underlying signals), for our primary aim is to argue that the features of this process are broadly applicable to personality assessment in ways that differ from the approaches traditionally taken. Some, possibly many, of the more technical properties of the low-level representations described by Shannon are also relevant for the assessment of individual differences in psychological characteristics (e.g., bandwidth-fidelity, the probabilistic nature of information signals, entropy, signal-to-noise ratios), although a full treatment of these topics is beyond the scope of this introductory work, which is about the broad associations between Shannon’s ideas and personality assessment. For more information, consider discussions by Ones and Viswesvaran (1996) and Hogan and Roberts (1996) regarding bandwidth-fidelity; Brunswik (1955), Jackson and Paunonen (1980), and Uher (2013) regarding the probabilistic nature of informative signals in personality; Golino et al. (2020) and Del Giudice (2020) regarding applications of entropy; and Cronbach and Gleser (1964), Nicewander (1993), and Revelle and Condon (2019) regarding signal-to-noise ratios in psychological assessment.

However, there is one important technical point in Shannon’s work (1948a) that is especially relevant to our ideas for advancing assessment. That is: in the absence of knowledge regarding the nature of a given “message” being conveyed (e.g., its content or size), Shannon proposed that estimation of its features should be based on the presumption that all messages in the possible set are equally probable, even though the possible set is, in practical terms, often very large (p. 393; Shannon, 1948a). In the absence of information about incoming messages, they are drawn stochastically from a very large set – effectively random and entirely unpredictable from the perspective of the receiver (aka the destination). This parallels the intuition in personality assessment that the set of *possible* expressions of behavior is also very large (Saucier, 1997), and – in the absence of *a priori* information about behavioral manifestation (including the individual, situation, and social and cultural norms to which the individual ascribes) – all behaviors are equally possible and therefore stochastic from the perspective of the observer. To be clear, behaviors are rarely perceived as random by the individual responsible for carrying out the behavior or by most observers; expectations typically reflect prior knowledge of density distributions of behavior (Jones et al., 2017). We return to this topic later, because it is fundamental to our call for a more information-theoretic approach to psychological assessment, but we raise it here to emphasize the difference between the diversity of human behavior within and across cultures and the small number of specific attributes that are typically evaluated with modern “omnibus” personality assessments (e.g., the Ten-Item Personality Inventory [Gosling et al., 2003; the Big Five Inventory 10 [Rammstedt & John, 2007]). In Shannon’s terms, this is the difference between a telegraph operator who accepts all messages from points unknown regardless of content or length and another that only accepts messages relating to a very small handful of pre-specified topics.

INFORMATION THEORY IN PERSONALITY

Figure 1: Shannon's schematic diagram of a general communication system

Returning to the process of message conveyance, Shannon's work provided a simple but elegant model for communication systems, and we find it useful for the conveyance of psychological signals as well. Figure 1 is a reproduction of this model from Shannon's original work (Kopp, Korb, & Mills, 2018; p. 381; Shannon, 1948a), illustrating the communication system components and their relation to one another. These include:

1. an *information source* that produces the sequence of messages to be transmitted, ranging in complexity from a simple vector (e.g., telegraphic code) to a multi-dimensional array of values that includes a time dimension (e.g., color video transmission with an associated audio channel).
2. a *transmitter* that converts the signal to a form that is suitable for transmission. This conversion involves sampling of the information source, quantification, encoding, and possibly compression (depending on the complexity of the message relative to the bandwidth of the communication system).
3. a *channel* through which the message is transmitted (e.g., a piece of paper, coaxial cable, radio frequency, beam of light). During transmission through the channel, messages are sometimes perturbed by *noise* of two types (stochastic noise and distortion), leading to *uncertainty* about the fidelity of the received message relative to the original encoding.
4. a *receiver* that converts the signal using the inverse of operations performed by the transmitter, specifically decompression (when needed) and decoding.
5. a *destination* that serves as the target or recipient of the message. Important characteristics of the object representing the destination will have a meaningful effect on the utility of the message once delivered and should be taken into account with respect to its conversion and transmission at all prior stages.

Following Shannon's initial elaboration of these preliminary concepts, the field evolved rapidly and, more or less, continuously over the ensuing 50 years. Without describing the technical details of these subsequent advancements in detail, it should be noted that they – and the technological innovations that they enabled – are instrumental to the information-theoretic applications of personality assessment described at the end of this chapter, to say nothing of the extent to which they have revolutionized many other aspects of modern life. One detail that should

INFORMATION THEORY IN PERSONALITY

be noted here, however, is the technical distinction made by Shannon and others with respect to discrete vs continuous systems: discrete systems are those where digitization of the signal occurs, whereas analog signals are passed through continuous systems. Both the digital and analog applications have proven relevant for personality psychology, in different ways.

Digital applications *seek to optimize the process of encoding and communicating* high-fidelity representations of psychological phenomena (i.e., assessment as an end unto itself). Transmission itself is the focus of these applications, and while the messages are used to represent or recreate analog phenomena, digitization is inherent to the manner of conveyance. In contrast, analog applications of information-theoretic approaches are suitable for *testing and refining models that aim to understand the analog processes of human behavior*. The focus of these applications is the behavior itself, and while empirical or simulated studies may involve some degree of digitization, the underlying processes are analog by nature. As we will emphasize, these are very different aspects of psychological research, especially in the domain of personality science.

Analog Applications

Analog applications of Shannon's ideas gained traction almost immediately in psychology despite misgivings by Shannon himself (Shannon, 1956), for many psychologists readily recognized that humans are (analog) information processors in the sense that phenomenological experience results from the perception of signals from the physical properties of encountered objects (light, sound, temperature, etc.; Campbell, 1958). These signals, and to a lesser extent the human systems for processing them, are deemed effectively continuous rather than discrete and are transmitted and stored in "lossy" formats (i.e., human communication and memory systems) that are prone to reductions in the signal/noise ratio over time.

Recognition of these underlying similarities led, in broad terms, to an information-processing revolution in cognitive psychology from roughly 1950 to 1970 (Miller, 2003; Xiong & Proctor, 2018), after which most of the cognitive psychology applications had fallen out of favor or been replaced with newer ideas (Laming, 2001; Luce, 2003). Still, several lasting contributions followed from the efforts of cognitive psychologists to incorporate concepts from information theory, the most notable being the suggestion of the 7 ± 2 rule to approximate the bandwidth limits of information processing (Miller, 1953, 1956). Others included contributions to research on different aspects of memory (Aborn & Rubenstein, 1952), hearing (Meyer, 1957), perception (Attneave, 1959), and attention (Broadbent, 1957).

A more familiar embodiment of the analog path for personality psychologists relates to the processing of information *about* personality specifically – person perception. Funder's (1995) Realistic Accuracy Model (RAM) of the process for arriving at accurate personality judgments is, to a considerable extent, an elaboration of Brunswik's lens model (1952), which itself owes a debt to Shannon's model (Cooksey, 2001). Subsequent work in this line has pointed directly to the relevance of information theory for personality judgments including the effect on judgment of information quantity and information quality (Letzring et al., 2006).

At a broad level, it is reasonably straight-forward to describe the process of person perception using the terminology of Shannon's system. To illustrate this point, see Figure 2 for a reproduction of Funder's (1995) RAM. The target personality attribute is the information source in

INFORMATION THEORY IN PERSONALITY

Shannon's case (see Figure 1).¹ In order to be "transmitted," features of the attribute must be relevant and available to the perceiver. In other words, there must be motivation and potential for the message to be transmitted from the source to the destination. Attributes that are not sufficiently relevant to the perceiver will not be transmitted because the channel (i.e., the focus of attention) will be occupied with the processing of other information. Similarly, signals of sufficient relevance will be transmitted but not received/perceived if they lack sufficient availability to the perceiver. In this case, the signal is not strong enough, as may occur if the attribute is weakly transmitted by the target or is made inaccessible by other competing signals in the environment. If the message is relevant and available, it remains possible that it will not be detected – either it is not received or it is inaccurately interpreted – due to attributes of the perceiver. The availability and detection steps in Funder's model both suffer from the potential for noise to be introduced in the transmission channel, as is also indicated between transmission and receipt in Shannon's model. For example, evidence of the attribute may only be intermittently available (as with stochastic noise) or availability/detection may be directly "distorted" by the target or perceiver (e.g., caused by conflicting goals of the target or misinterpretation by the receiver). The final step of Funder's model extends beyond Shannon's channel somewhat, as it allows for the possibility that some signals may be received without being put to use. Just as inboxes often overflow with mail, there are sometimes more signals received about a target's personality than can be taken into consideration at one time.

Figure 2: Funder's schematic diagram of accurate personality judgment

In fact, the experience of being overwhelmed by personality-relevant signals is likely common and warrants further consideration. Humans are highly social animals, consistently exposed to large samples of information-generating behaviors, often from multiple individuals at once, leading to an overload in our ability to process them all in real time. Even under these demanding circumstances, humans typically perceive information produced by these behaviors and shape it into judgments of personality without much effort, or even awareness. In this sense, we are constantly "assessing" the personalities of our close friends and family, more-distant contacts, new acquaintances, strangers, celebrities, and even ourselves. Though sometimes overwhelmed, the communication channel of personality assessment is nearly always open, and individual differences in the processing of these incoming personality-relevant signals even *contribute* to many important features of personality. Consider, for example, differences in the extent to which people seek out

¹ Also, the distal object for Brunswik (1952).

INFORMATION THEORY IN PERSONALITY

social interaction of various types, and differences in various cognitive and affective reactions to ambiguous signals from others.

Similarly, the personality judgment literature has sought to improve our understanding of various aspects of the analog process connecting the “emissions” of these information-generating behaviors to a huge range of personality outcomes. This includes work that (1) distinguishes personality from species-typical characteristics of human behavior (McAdams & Pals, 2006); (2) attempts to identify moderating factors in the perception of personality (Edwards & Von Hippel, 1995; Todorov et al., 2015); (3) acknowledges the interplay between these information-generating behaviors, manifestations of personality, and features of the situations in which they are expressed (Fleeson, 2004; Funder, 2006); and (4) seeks to classify the salient features of each broad category of the components (the behaviors, situations, and personality) involved in information signal emission. The extent of progress on this last front varies considerably, from decades-long efforts to specify parsimonious models of personality (Goldberg, 1993a) to relatively recent attempts to specify the generalizable features of situations (Rauthmann et al., 2014).

We provide a more thorough discussion of the relationship between everyday judgments of personality and formal personality assessment after reviewing the history of digital applications of IT and personality. For now, as an interim summary, we emphasize that the analog applications of IT were most rapidly embraced in cognitive psychology, with a more indirect but long-lasting effect in personality psychology via the sub-discipline of person perception. Advancements in our understanding of person perception, as we will argue, are relevant for personality assessment in the sense that these informal, analog, and often unconscious judgments are the reality we should be aiming to capture with novel digital approaches to personality assessment.

Digital Applications

The prospect of applying Shannon’s ideas about the most efficient means of conveying digitally encoded messages was only considered for a few years before Lee Cronbach (1955a) declared it incompatible with the aims of psychological assessment. This outcome likely caught Cronbach’s closest colleagues by surprise, for his initial views about the potential utility of information theory were enthusiastic. Shortly after the release of Shannon’s 1948 publications, Cronbach successfully garnered funding from the Office of Naval Research “to examine testing problems in terms of Shannon’s information theory” (Cronbach, 1952), focusing in particular on the relationship between bandwidth and fidelity. His seminal work on coefficient alpha (Cronbach, 1951) during this era also includes an extended discussion of “Shannon information” as a coefficient for quantifying the amount of information in a set of messages/signals. Over time however, his enthusiasm gave way to concern about a perceived incompatibility between the *application* of information theory ideas and the nascent standards of psychological assessment (Cronbach, 1953). He articulated this concern at a conference on information theory applications in psychology in 1954 — one of three conferences on the topic that year (Quastler, 1955) — and in a subsequent chapter summarizing his views (Cronbach, 1955a). The case in favor of an information theory approach was closed before anyone else had chimed in.²

² Ironically, Funder has noted elsewhere (Funder & West, 1993) that research on accurate personality judgments was brought to a “screeching halt” by Cronbach during this same era. Though Cronbach’s harsh critiques of prior research on the topic (Cronbach, 1955b; Gage & Cronbach, 1955) were not well-understood at the time (nor subsequently;

INFORMATION THEORY IN PERSONALITY

The nature of Cronbach's concern

Cronbach's issues with the application of information theory in psychological assessment include both a major concern and several minor complaints. These lesser points are presented in a hasty and confusing manner (Cronbach, 1953) so we do not take them up in this review, though we feel it is necessary to acknowledge them for the sake of transparency. His primary issue is that the formulae presented by Shannon (1948a):

... apply precisely only when patterns of inputs can be encoded simultaneously, a condition not fulfilled in our testing problem. As approximations, the formulas express the number of standard independent items required per person to classify him, before and after testing. But this has meaning only if tests are used sequentially, with different persons given different numbers of items. Hence, there will be few occasions to treat data by the formulas [of Shannon]. (p. 41, Cronbach, 1953)

In essence, Cronbach is saying that Shannon's model for the digital transmission of informative signals shown in Figure 1 (and the formulae that follow from it) is incompatible with the standard model of psychological testing in use at that time. He argues that Shannon's ideas would only be relevant for psychological testing if it were possible to capture the full psychological signal in a single message – in his words, simultaneous encoding of *patterns* of inputs. This contrasts with the standard approach of psychological testing, where data are digitally encoded one item at a time in a structured order. In Cronbach's era (and even still today), a relatively small number of constructs were assessed in a given testing session, with several items for each construct. In other words, the incompatibility stems, in his view, from the fact that it is not possible to exhaustively assess the individual systematically and comprehensively, across many constructs, in a single assessment (i.e., “message”).

To address this concern, it is useful to revisit the components in Shannon's system, especially with respect to the encoding and decoding steps that are more relevant for digital applications than analog cases. The information source (Step 1) produces a sequence of messages that are encoded by the transmitter (2). In other words, features of the messages to be relayed are atomized into some essential elements. Shannon (1948a) elaborates on the atomization process in great detail though we can effectively summarize this idea by pointing to examples such as the atomization of sentence-length messages being sent via telegram as a string of letters/words or video images being sent through the web as a string of data packets that are re-assembled by the receiver (e.g., a router or video player). Regardless of their form, the elements are transmitted through the channel (3) to the receiver (4) where they are more-or-less faithfully re-assembled, depending on the limitations of the channel components and the introduction of noise during transmission. With primitive (low-bandwidth) communication technology of the mid-20th century, faithful transmission and re-assembling of detailed content was often slow. Allowances were thus made, in practical applications, to keep transmissions short by minimizing the information to be transmitted. Importantly, information scientists working in the tradition of Shannon focused their research on improving the system of *signal transmission* to allow for more efficient transmission of ever-increasing amounts of information rather than focusing on the minimum amount of information needed to retain a reliable signal. Shannon's approach was also remarkably successful:

Funder & West, 1993), his main point (1955b; Gage & Cronbach, 1955) was that the field suffered from inadequate theoretical specification of sufficiently broad latent variables; a point that indirectly relates to his dismissal of digital applications of information theory (Cronbach, 1955a).

INFORMATION THEORY IN PERSONALITY

after several decades of progress it is now possible to faithfully reproduce (i.e., “model”) life-like visual and auditory experiences virtually instantly across vast distances.

The latter approach – the path not taken by information scientists – focused on parsimonious data capture, and was pursued with great success by Cronbach and colleagues in the development of psychological testing methods. A (too) short summary of the most durable tenets of Cronbach’s legacy would be that psychological testing and measurement necessarily involve the modelling of latent constructs with few composite variables (Cronbach, 1960) that can (and should) be evaluated in terms of reliability (Cronbach, 1947, 1951) and multiple forms of validity (Cronbach & Meehl, 1955). In conjunction with the constraints of limited testing time (noted by Cronbach, 1953), the use of composites and the emphasis on internal consistency, in particular, all contribute to the prioritization of parsimonious modeling in psychological testing. To meet this priority, the amount and content of data to be collected is nearly always prescribed in advance for each person tested. This is in contrast to the information theory approach where the goal is to identify prominent (i.e., salient or unexpected) features of the individual, without prescribing the amount or even the content of the data to be collected in advance. The fact that this idea may seem radical to many psychologists today is a testament to the success of psychometricians like Cronbach in the mid-20th century.

The two approaches are more compatible than Cronbach suggested, as both seek to encode, transmit, and interpret (i.e., decode) signals about psychological content. The traditional psychometric testing approach encodes only specific features of the signal using testing instruments that are familiar to most psychologists – brief, fixed-form, full-information, survey-based measures administered in controlled environments. Widely-used, modern examples include the Ten-Item Personality Inventory (Gosling et al., 2003) or the Big-Five Inventory (John & Srivastava, 1999). But many other types are possible, including those which are not ideally suited for the psychological testing administrations that Cronbach had in mind in his time. Personality attributes lead to the production of signals that can be digitally encoded through any number of technologies. These include a diverse range of survey methodologies (e.g., longer forms, randomized item administrations, planned missingness designs, observer reports, diverse situations and settings of administration) and non-survey-based approaches (e.g., passive data collection via electronic audio and video recording, digital footprints). Once encoded, the transmission of the signal through the channel is uneventful in assessment contexts (data are stored electronically on a server), though it typically does need to travel from the encoding equipment to the decoder. Noise is introduced at both the encoding and decoding steps, and possibly through the channel itself. Once decoded, it has arrived at the destination where the results can be interpreted (typically, by the psychologist and/or data analyst).

With the benefit of hindsight, Cronbach’s dismissal seems an understandable but unfortunate symptom of his role in the psychological testing milieu around 1950. We feel that the circumstances surrounding Cronbach’s claims are worth reviewing, as they help to explain why information-theoretic approaches have not been invoked over the last 70 years and point to ways in which they might be. This is done in the following 3 subsections on (1) the role of psychological testing in the advancement of personality assessment, (2) the primacy of latent variable theory in personality testing, and (3) the meaning of “information” for personality assessment.

INFORMATION THEORY IN PERSONALITY

1. The role of psychological testing in the advancement of personality assessment

In retrospect, it seems clear that one of the factors contributing to Cronbach's dismissal was the gestalt view of psychological *testing* during this era. This view – a general understanding of best practices for psychological testing – was beginning to coalesce by the early 1950s, and Cronbach was one of the most visible leaders of this burgeoning industry with promising growth prospects. To explain the gestalt view, it helps to briefly summarize the history of testing before the post-war era.

One of the most critically important innovations in testing was the use of questionnaires for data collection, and this development is often overlooked by virtue of having such primacy in personality psychology, especially today. Cronbach did not take this innovation for granted, and frequently called attention to the ingenuity of questionnaires (Cronbach, 1960, 1970).³ He explicitly defends the use of questionnaires over direct observation because surveys “avoided the labor and delay involved in direct observation of behavior” in the many “situation[s] where individual interviewing of every man was totally out of the question” (p. 465, Cronbach, 1960). For further evidence of this consequential idea, see Cronbach & Gleser (1965) and Cronbach (1970).

Many “best practices” in psychological testing evolved from this fundamental idea that questionnaires are a work-around for behavioral observation, and the effects were relevant for the evolution of theory as much as methods. The first formal personality inventory — the Woodworth Personality Data Sheet (WPDS, Woodworth, 1917) — was commissioned to use the questionnaire approach to evaluate military recruits for emotional stability (Cronbach, 1960; Gibby & Zickar, 2008; Goldberg, 1971). The questions were derived from the list of symptoms covered in psychiatric interviews (Poffenberger, 1962). The WPDS was never copyrighted and served as the basis for several subsequent tests (Gibby & Zickar, 2008), each of which borrowed heavily from earlier tools. Thurstone, for example, acknowledged the recycling of content explicitly in stating that his Personality Schedule (Thurstone & Thurstone, 1930) “was compiled mostly from several shorter lists already published, including Woodworth’s Psychoneurotic Inventory [an earlier name for the WPDS, (Woodworth, 1917)], House’s monograph on this subject [the Mental Hygiene Inventory, (House, 1927)], Laird’s schedules of questions [the Colgate Tests of Emotional Outlets, (Laird, 1925)], Freyd’s list of questions [about introversion and extroversion, (Freyd, 1924)], and Allports’ list of questions [about ascendance-submission, (Allport, 1928)]” (p. 1, Thurstone & Thurstone, 1930). All of the questions in the WPDS were included in Thurstone’s measure without revision!

This pattern continued into the post-war era, overlapping with Cronbach’s own ascendancy. The most widely used measure of that period was the Bernreuter Personality Inventory (BPI, Bernreuter, 1931); the content of this inventory was acknowledged to be a subset of Thurstone’s

³ Cronbach credits Galton for development of the self-report questionnaire (Cronbach, 1960; Galton, 1884; Galton, 1869). It seems worth noting that Galton’s *The Measurement of Character* (1884) is commonly cited in the personality literature as the origin of the Lexical Hypothesis (Allport & Odbert, 1936; Goldberg, 1990, 1993a) on account of a passing comment regarding the author’s consultation of the dictionary in an attempt to “gain an idea of the number of the more conspicuous aspects of the character” (p.181, Galton, 1884). The next two paragraphs of this same reference make more explicit suggestions for the advancement of personality assessment, though he never directly advocates for the lexical approach. Instead, he proposes the empirical mapping of character through two paths: (1) assessment via high-stakes testing (specifically, interviews or tests that “elicit some manifestation of character,” presumably including surveys) and (2) more ordinary sustained observation of small frequent behaviors (something akin to the information theory approach we elaborate below).

INFORMATION THEORY IN PERSONALITY

aggregation of others' items [Bernreuter (1933); Gibby & Zickar, 2008].⁴ Though rarely referenced today, the BPI was administered to millions of test-takers in the 1930s and 40s, peaking at more than 1 million in 1953 (Whyte, 1956). Several competing measures were close behind, including the business-focused Humm-Wadsworth Temperament Scale (Wadsworth, 1937, 1936) and several newer entrants that remain familiar today: the Minnesota Multiphasic Personality Inventory (Hathaway & McKinley, 1940), the Myers-Briggs Type Indicator (Myers, 1945), the Guilford-Zimmerman Temperament Survey (Guilford & Zimmerman, 1949), and the 16 Personality Factor Questionnaire (Cattell & Eber, 1950).

This review is more than just a history lesson; it provides a sense of the landscape of psychological testing in Cronbach's era and supports more specific claims about perceived best practices in methods. As noted, one was the strategy of using behavioral questionnaires (mainly, self-report) rather than more taxing and time-consuming approaches to behavioral observation. Following from this, methods for digitized encoding (scoring and coding) gained consensus – in some ways, it was the urge to digitize that drove the use of checklists and Likert-like response scales – as did the development and utility of increasingly sophisticated statistical techniques. It is no coincidence that several statistical methods were developed or vastly advanced by psychologists working to develop better testing methods -- psychometricians. This includes the correlation coefficient (Rodgers & Nicewander, 1988; Spearman, 1904a), factor analysis (Cattell, 1946; Mulaik, 1987; Spearman, 1904b; Thurstone, 1931), and evaluations of reliability (Cronbach, 1947, 1951) and validity (Anastasi, 1950; Cronbach & Meehl, 1955).⁵

The point is not that Cronbach should be faulted for a perspective that was influenced by the milieu of his era but rather that his perspective shaped his dismissal of an information-theoretic approach that did not obviously fit into the features of personality assessment that were relevant for psychological testing. Before and during the 1950s, the psychological testing industry was finally beginning to enjoy the benefits of industrial, military, and educational applications of psychometric theory. Cronbach was a key player in the informal alliance – the latent variable theory-psychological testing complex – that had evolved during the decades of the mid-20th century between psychometricians and the organizations that made use of psychological testing. Indeed, the tasks of developing and administering psychological assessments were often carried out by the same individuals. Like many such complexes (i.e., the military-industrial complex), the benefits of this alliance were (and continue to be) mutually reinforcing for both sides but also serve to reduce the incentives for developing divergent approaches. Indeed, the informal codification of procedures for psychological test development unfolded rather quickly under the guidance of a small group of quantitatively oriented psychologists. Many of these individuals were funded by governmental agencies and similar organizations to develop psychological tests for use in specific applications, and their influence has had a long-lasting impact on personality assessment.

⁴ Allport threatened legal action against the owners of the BPI, while also acknowledging that Bernreuter's measure was an improvement upon his own (Gibby & Zickar, 2008). The stark contrast between modern-day concerns about copyright infringement and the liberal sharing of content during the early years of test development is discussed in greater detail by Deary and Bedford (2011).

⁵ Academic and intellectual lineage is relevant to this point, for Cattell was a student of Spearman and Cronbach a student of Thurstone (who was still very active in the early 1950s).

INFORMATION THEORY IN PERSONALITY

2. The primacy of latent variable theory in psychological testing

Building on recognition of the latent variable theory-psychological testing (LVT-PT) complex, it is also necessary to consider the role of latent variable theory in Cronbach's dismissal of information-theoretic approaches. Are these topics incompatible? In short, no. But, to answer this question more thoroughly, it is first necessary to clarify that our use of the label "latent variable theory" draws upon the framing of Borsboom (2008). That is, we use this term in reference to the broad framework of ideas and practices that relate to the use of latent variable modeling as a procedure for mapping the relation between theoretical constructs and empirical data. While there are many types of latent variable models (mostly differentiated by the involvement of discrete vs continuous variables), they share the same goal of using a regression function to relate the manifest (observed) variables to those which are inferred (unobservable). In this way, latent variable theory enables the testing, comparison, and refinement of psychological theories by modeling observed data. For a thoughtful treatment of the assumptions, implications, and applications of latent variable theory, Borsboom's (2008) contribution is recommended.

The relevance of latent variable theory to the current discussion stems from its use in test development, most familiarly with techniques like factor analysis and principal components analysis. These tools are invoked to *reduce* large amounts of information down to a manageable (i.e., parsimonious) number of broad concepts that are central to the topic(s) under study. The utility of these data reduction techniques is hard to contest, for they have advanced our understanding of many psychological domains, including several that are central to personality such as the structure of individual differences in temperament (Cattell, 1947; Goldberg, 1993b; Norman, 1963), cognitive abilities (Carroll, 1993; Cattell, 1987), interests (Holland, 1959; Prediger, 1982), and much more. For these domains in particular, assessment tools intending to capture broad ranges of content (e.g., personality traits) have typically been derived from the reduced, factor analytic models of latent constructs that make use of composite variables and prioritize parsimony.

Problems creep in, however, when these techniques are used to develop tests that are subsequently widely adopted as personality assessments in research contexts with too little recognition of the information that gets ignored. This includes content that was omitted from the outset of test development as well as content that was originally included but later dropped because it did not explain sufficient variance in the validation process (Saucier, 1997). It also includes information that is collected as part of the test but ignored as allegedly unreliable noise (McCrae, 2015), as is prescribed by the latent variable approach advocated by Cronbach. To be clear, the exclusion of this content by test developers is intentional, reasonable and typically well-acknowledged. Yet, the benefits are diminished when these tools are used in research contexts that differ considerably from the testing situation and/or the validation setting. Consider, again, the small number of pre-structured attributes evaluated with very brief, omnibus personality assessments (e.g., the Ten-Item Personality Inventory [Gosling et al., 2003; the Big Five Inventory 10 [Rammstedt & John, 2007]); these measures are among the most widely-used for personality assessments in research contexts. The question is not whether the measures are technically consistent with the latent variable model in which they are rooted but rather their ability to reasonably serve as assessments of personality as a broad phenomenon. Conscientiousness, for example, is measured by the extent to which one is "dependable and self-disciplined" and "disorganized and careless" (Gosling et al., 2003). Many features of this trait family are missing entirely such as "the propensity to be self-controlled, responsible to others, hardworking, orderly, and rule abiding" (Roberts et al., 2009). Many more might be included from outside the boundaries of the familiar Big Five traits, and

INFORMATION THEORY IN PERSONALITY

each of these features could be measured independently rather than indexed. An information-theoretic approach might include behavioral markers and/or contextually specific variables that are not even pre-specified in the same manner as standard survey instruments.

This difference in the use of pre-specified variables reflects a deeper distinction between the two approaches. Many, perhaps even most, of the psychological scales developed over the history of psychology have been created with a heavy reliance on theory from the outset. Consider the Myers-Briggs Type Indicator (Myers, 1945), for example, which is based on one team's interpretation of Jung's previously untested theory about personality (Jung, 2016). The utility of this measure is severely impaired by this theory-heavy approach to design. On the other hand, joint application of the latent variable and information-theoretic approaches can be uniquely powerful, as exemplified (somewhat imperfectly) by psycholexical models of personality. The Big Five framework is vastly more valid than the MBTI because it began with a broad sampling of the universe of personality-relevant human attributes. A more optimal (if less pragmatic) implementation of the two approaches might have used even more than the 500-600 trait-descriptors (reported in Goldberg, 1992) and these would have been assessed relative to a wide range of situational contexts and a maximally diverse sample of respondents. Note that we do not mean to argue that the information-theoretic approach precludes the use of data reduction techniques or subsequent invocation of latent variable modeling to evaluate the mechanisms underlying psychological phenomena. To the contrary, the utility of both theories may be improved when used in conjunction: information-theoretic approaches that seek to broadly characterize phenomena and latent variable approaches for positing, testing, comparing, and refining causal models. The problem only lies with the exclusive use of latent variable theory approaches for psychological assessment

3. The meaning of information for personality assessment

In Shannon's framing (1948a), the information-theoretic measure of information has subsequently been called Shannon information or, more frequently, entropy. This name is due, in part, to its rough equivalence to the probability equation for thermodynamic entropy. This poses a confusing problem, in retrospect, for the terminology of information theory approaches is easily conflated with a large body of testing-related research conducted during the same era (roughly 1948 to 1955; see Lord [1953]). The aim of this and subsequent research on "item response theory" (IRT) was to specify the amount of psychometric information provided about a specific trait level based on the pattern of responses to a scale or single item. The functions used to model the psychometric information in IRT are generally known as Fisher information functions (Markon, 2013), causing further difficulty for these were first described (Fisher, 1922) more than 25 years ahead of Shannon's work, and perhaps earlier in other forms and applications (Aldrich, 1997).

Put simply, "information" is an unfortunately vague term, and one with a history of use in psychological test theory relating to the estimation of a latent trait level on the basis of a given response to a measure of that trait. Consistent with the pre-specification of variables in traditional psychological testing, this usage of the term information depends on knowing what one seeks to measure *a priori*, and it further assumes that the test being given to assess the targeted construct is both valid and specific to a particular dimension (e.g., a dimension of a latent construct). The basic logic is to situate a test-taker's responses relative to the underlying dimension on the basis of prior knowledge about the distribution of responses. It is a comparison of two possible states (probability distributions) and is therefore sometimes referred to as "relative entropy" (Rioul, 2018). In short, the approach being advocated by Cronbach and his contemporaries (whether classical test theorists or

INFORMATION THEORY IN PERSONALITY

those laying the foundation for IRT in the early 1950s) was to focus psychological tests on a small number of pre-specified latent constructs. In so doing, they focused only on the extent to which test-takers compared to others on each of these constructs. This was often done independently; that is, without comparison across multiple constructs simultaneously.

Shannon's entropy, by contrast, can be thought of as an absolute measure; a measure of the amount of information gained by each message. Alternatively, this is sometimes framed in terms of informational complexity or surprisal value; that is, the probability of the message given the context. These ideas point to a focus on the most uniquely identifying features of the individual — and these may often *not* be captured by the pre-specified latent constructs. Of course, this poses a problem in cases like those described by Cronbach where the amount of information that can reasonably be captured is limited relative to the full range of possibilities. In these cases, it is unlikely that the most identifying features for any given individual would be collected by chance. Fortunately, as we discuss in the next section, the confluence of several developments since 1955 have begun to feasibly address this concern by allowing for much less limited data collection than Cronbach could have anticipated, including some types that are entirely passive.

In summary, our point is not that Cronbach's dismissal of information theory principles was inappropriate at the time — it probably was not — but rather that it is time for his rationale to be reconsidered. The boundaries of personality science extend, inherently, beyond the scope of existing psychological testing tools (Möttus et al., 2020). Exploratory approaches should pursue methodological advances that are not based in existing assessment paradigms, and these innovations should not be limited to behavioral questionnaires. Personality psychologists who embrace the spirit of information theory should seek to maximize the information (Shannon information or entropy) captured across a large number of narrow psychological individual differences (Condon et al. 2020). With some irony, we recognize that this has only become possible thanks to the most recent technological achievements of the information age.

Invoking Information Theoretic Approaches in Personality Assessment

Our advocacy for a more information-theoretic approach involves a shift of focus away from a priori-imposed parsimony in personality assessment, moving instead towards a more precise representation of the diversity of individual differences expressed in the real world. Progress in this direction is likely to occur as a by-product of the increasing ability to collect more and more data, and these technological advances can also bring about the opportunity for theoretical advancement beyond traditional approaches. This shift can be about more than data collection, extending to include new analytic methods and personality descriptions across more than the familiar parsimonious dimensions. In other words, we are not just calling for *more* data; we also need and can develop new and more flexible frameworks for representing and thinking of the data (Möttus et al., 2020).

Importantly, we are not advocating against further development of the traditional psychometric approach advanced by Cronbach and others. Rather, we are arguing that Cronbach and others focused only on one specific coding system for personality (latent variable modeling), and dismissed the information theoretic approach for reasons that are not always relevant in modern research contexts. As we have already discussed, the synergistic nature of the latent variable theory-psychological testing complex was no coincidence, for the emphasis on parsimony and improved signal-to-noise ratios grew out of the practical demands of testing (limited time and strong

INFORMATION THEORY IN PERSONALITY

motivation to maximize accuracy at the level of the individual). An information theoretic approach would be much more flexible. It could allow for a broader range of assessment, including both greater breadth of content (higher bandwidth) and a greater diversity of information types, including a wide range of behavioral and situational variables across multiple occasions (a la Brunswik [1955]).

Emphasizing the needs of researchers over test administrators

A specific starting point stems from one of Cronbach's claims about information theory being relevant only to conditions that are not met by his "testing problem" (p. 41, Cronbach, 1953). The primary challenge with testing is to efficiently classify large numbers of individuals according to attributes that have been deemed diagnostic, whether clinically or for predicting performance in military, occupational, and educational settings (Meehl, 1954; Revelle, Wilt, & Condon, 2011). In other words, create a test that balances the needs of scalability across test-takers, efficiency in administration and interpretation, and utility for each individual (this requires retest reliability and validity; Condon et al., 2020). As previously mentioned, an early and consequential decision was made in the testing arena to use fixed-length questionnaire forms (with each questionnaire prompt coming to be known as an item). When wrestling with the prospect of using an information-theoretic approach, Cronbach offers the following example:

Suppose we have 50 binary test items, and 50 people. I get 50 bits of information, if I give 50 items to one person; or I give one item to 50 persons. ... Now hypothetically, the configuration of 50 responses might help me decide if one person was schizophrenic; I could use the information all together in making one decision. But with one item per person there are only 50 facts to be considered separately, each for a decision about one person. There is no problem on which these data as a configuration or single message bear. The message about one person and the message about 50 people occupy equal message space; but only a small part of the information about the configuration of people is functional. (Cronbach, 1953)

This false dichotomy is well-suited to his viewpoint. The data collector is limited to a small amount of data collection (here, 50 binary digits or "bits") and only two all-or-nothing options; one captures a little information about many people, the other a somewhat larger amount about only one person. For test administrators, the latter is preferred for it does a better job of balancing the needs of the testing context – for schizophrenia, in this example, but this could be generalized to other psychological phenomena, including those with higher base rates or even Gaussian-like distributions in broad populations (i.e., personality constructs). However, it is not at all certain that the latter option is better for personality researchers, especially when considering more realistic data collection parameters.

Consider, for example, how the situation changes when it becomes possible to collect many thousands of bits of information. Today, sample sizes in personality research will often contain 150,000 bits and sometimes much more. This is equivalent to 3 bits per item (5 to 8 response choices) for 100 items and 500 participants. Data from the Eugene-Springfield Community Sample (Goldberg & Saucier, 2016) contains more than 10 million bits and the data reported in Johnson (Johnson, 2014) contains approximately 500 million bits or 0.625 gigabytes.⁶ The scientific literature

⁶ Though very large relative to the data sets collected by personality researchers historically, it is important to keep in mind – especially when considering the prospects for information theoretic approaches – that these are trivial relative to data sets collected in other scientific disciplines. For perspective, 0.5 GB is equivalent to about 3 minutes of high-quality digital video (DV/AVI format). Approximately 4.0×10^{11} GB are collected each year at CERN.

INFORMATION THEORY IN PERSONALITY

provides strong evidence that many researchers prefer to collect data from large samples of participants rather than use a case study approach that seeks to characterize a single participant across all imaginable questionnaire items. A more important observation is that most researchers choose to use a blended approach, one that strives for high analytic power (based on large sample sizes) but uses the shortest and most parsimonious assessments possible. The blend adapts the LVT-PT approach to better suit the needs of researchers, though the benefit of collecting much more information (bigger samples) accrues to higher levels of measurement precision rather than breadth.

The prospect of broader adoption of information-theoretic approaches among personality researchers points to a wide range of possibilities, including those suggested by Cronbach's contemporaries. In Brunswik's work on Representative Design (1955) – a component of his broader Conceptual Framework for Psychology (1952) – he called for much closer scrutiny of the effects of the environment on personality phenomena studied under testing (and experimental) conditions. Brunswik meant this quite broadly, calling for sweeping improvements in methods including data collection on the environmental features at the time of assessment, multiple assessments across heterogeneous environments, and greater sampling of items across assessments (Brunswik, 1955). Brunswik distinguished these changes from more familiar notions of simply moving assessments into “real-life circumstances” (i.e., ecologically valid conditions); he sought to emphasize the mechanistic effects of situational variables. Perhaps unsurprisingly, Brunswik's suggestions were not readily embraced by his contemporaries (Leary, 1987), though many did acknowledge being influenced by his ideas, despite their intractability at the time.

Figure 3: A revision of Cattell's data box, with Cronbach's dichotomy of options (indicated with arrows A and B).

Cattell elaborated similar ideas with his “data box” (1966), a metaphor he had first proposed 20 years earlier (1946). The data box was used to illustrate the need for descriptive research in personality on the associations among persons, variables, and occasions. Figure 3 (occasion 1) depicts the essence of Cattell's suggestion, with Cronbach's earlier example included (his dichotomy indicated with arrows A and B). Brunswik's suggestions were only partially captured in Cattell's

INFORMATION THEORY IN PERSONALITY

original 3D box metaphor (persons by variables by occasions), in that he called for multivariate time-series data collection within persons that also measured features of the environment at each occasion, as shown in Figure 3. Truly representative designs, according to Brunswik (1955), would further account for multiple perspectives, including the target, multiple informants, and objective behavioral markers. The fifth dimension of perspective is not shown in Figure 3, though it is represented, in some sense, by its consideration across multiple raters (of targets, across variables, and multiple situations, over time).

It is important to acknowledge that these methodological suggestions by Cattell and Brunswik do little *by themselves* to invoke information-theoretic approaches. Yet, they provide a means of framing the diversity of personality-relevant signals to be encoded, one that more realistically suggests the nature of the “problem” from the perspective of personality researchers rather than psychological testing administrators.

Next steps

To push these ideas more obviously into an information-theoretic perspective, personality science will need to undertake investment in several “slow science” projects (Reischer & Cowan, 2020). Though the prospect of achieving representations like those shown in Figure 3 have been greatly improved by recent technological innovations, they remain daunting and beyond the reach of small, independent research teams. Given this, there is a great need for collaborative approaches across multiple labs and involving personality scientists with diverse training, theoretical perspectives, and backgrounds. Several of the required projects should be expected to unfold over many years, given their scope and the hope of collecting data across multiple occasions. A model for these collaborations is provided by the aforementioned Eugene-Springfield Community Sample (Goldberg & Saucier, 2016), the data collection project associated with the International Personality Item Pool “collaboratory” (Goldberg, 1999).

What are the aims of these projects? The most formidable (and possibly the most disputatious) is to atomize the various types of signals about how individuals can differ into their essential elements. This does not need to be as complicated as it sounds. Some progress has already been achieved along these lines in the historical work of identifying the “atoms” of personality descriptors in language (i.e., Allport & Odbert, 1936, Norman, 1967, Ashton et al., 2004). A prospective example of this might include collaborative “bottom-up” development of assessment taxonomies across the range of domains relevant for personality-contexts, as suggested by Condon and colleagues (2020). It remains an open question whether it is feasible to pursue the development of a singular, exhaustive taxonomy that integrates the many domains of psychological individual differences (temperament/character, interests, values, worldviews, strivings, motivations, abilities, etc.; Condon, 2014) or if the preliminary development of many such taxonomies is more reasonable in the near term.

A full account of the steps needed for a bottom-up approach to assessment remains beyond the scope of the current work. In any case, these likely vary across domains of content. Efforts are currently underway to begin such development in the domain of content relating to personality items like those in the International Personality Item Pool (though not limited to these exclusively). This initiative – involving both authors of this work – has not yet progressed beyond the stage of developing iterative procedures for consideration by the field more generally (Condon et al., 2020; Möttus et al., 2020). These are iterative in that the goal – identifying an *essential* set of assessment

INFORMATION THEORY IN PERSONALITY

content that is defensibly exhaustive without being excessively redundant – can only be achieved with multiple rounds of empirically-informed refinement. These rounds would optimally involve data collection similar to the methods suggested in Figure 3.

An obvious challenge to initiatives such as these relates to the difficulty of large-scale data collection. Recruiting and retaining large numbers of participants is only the first hurdle (though see our comments below regarding the potential to combine samples across research groups and paradigms as in a mega-analysis). An equal challenge relates to the need to collect more data than participants are willing to give in a single setting. One option is to spread the data collection across many waves (as was done in the Eugene-Springfield Community Sample; Goldberg & Saucier, 2016), but this introduces new problems. A more efficient alternative would incorporate a planned missingness design (Revelle et al., 2016). For example, one might collect data from 50 variables randomly sampled from a much larger pool, perhaps many thousands (Condon, 2019). This approach would be fruitless if used with sample sizes common in the 1950s, or if research teams are dealing with inconsistent groupings of variables. Yet, the power of this technique is magnified when scaled to many thousands of participants within a study and/or across multiple research teams.

Additional aims for these projects follow from the benefits of consensus around more detailed assessment frameworks such as moving from the Big Five-centric assessments to those that account for the hierarchical organization of personality, from few broad traits to numerous more specific ones (Condon et al., 2020). Several suggestions follow from information-theoretic techniques including (1) evaluations of the informational content that follows from the administration of variable subsets to independent (and demographically distinct) samples of participants, (2) across situations, (3) occasions, and (4) perspectives. The details of this suggestion – based on entropy (aka Shannon information in this case) – are left for subsequent work, but the basic notion is to evaluate differences in the overall amount of information across studies by comparing the entropy of individual items or item subsets. Evidence for either would indicate differences in the expected probabilities of signal magnitudes, as might be expected given differing circumstances across studies. Further studies of the properties of transmission of personality-relevant information signals might also make use of more traditional psychometric properties. For example, evaluations of the extent to which signals are consistently encoded/decoded over time will make use of (5) signal-to-noise statistics, especially test-retest coefficients. Similarly, qualitative methods for evaluating the introduction of noise would consider the consistency of signal detection and utility based on the (6) translatability, (7) social desirability, and (8) literacy levels of item content.

Most of the next steps described in this section have focused on applications with survey items, but this need not be the case in practice. In our view, one of the most consequential results of Cronbach's failure to recognize the potential of an information-theoretic approach has been the long-standing primacy of questionnaire-based methods over behavioral observation. Surveys will continue to be the dominant method of data collection in personality in the near term, but the increasing adoption of more passive assessment techniques suggests this dominance may not last. Examples of these new methods include digital footprint data collected from social media, electronic health records, and passive sensor data (e.g., Cooper et al., 2020; Harari et al., 2020; Wiernik et al., 2020; Hall & Matz, 2020; Stachl, Au et al., 2020; Tay et al., 2020).

These methods may enable the evaluation of new considerations – such as the transmission of covert signals (i.e., information signals that can be accurately transmitted and received by intended

INFORMATION THEORY IN PERSONALITY

targets but not by unintended targets; Smaldino, Flamson, & McElreath [2018]) – and new challenges (thorough discussions of these are provided by Girard & Cohn [2016] and Harari, Müller, Aung, & Rentfrow [2017]). Data privacy concerns loom large among these challenges, but new decentralized approaches to digital identity management via blockchain and similar technologies offer some promise for the eventual possibility of securely sharing massive amounts of personality-relevant data (Wang & De Filippi, 2020).

Importantly, evaluations across studies using methods like those described above would not necessarily be limited to individual research groups, as is the norm currently. Consensus regarding the atomization of personality signals would hasten (and arguably, enable) the standardization of variables. In turn, this would increase the pace of personality research (Goldberg, 1999), in part by increasing the motivation to pursue information-theoretic approaches. Prior attempts at standardization in personality have mainly focused on the important aspect of pushing survey content into the public-domain (Goldberg, 1999; Armstrong et al., 2008, Condon, 2019), but this is not sufficient. Agreement about the lowest-level units would lead to much more detailed standardization. In the case of variables, for example, this might include standardized variable labels, response choices, item stems, and recall periods (Condon et al., 2020). Similar examples might be given for environmental criteria (in the situations dimension) or variable specific time intervals between administrations (for occasions).

In sum, the atomization of personality signals is not an end unto itself, but a requisite step in the more efficient assessment (i.e., transmission) of psychological individual differences. It is with some irony that the next step after achieving tentative consensus around the boundaries and operationalizations for these essential elements likely involves the need to fill in the “nomological network” often attributed to Cronbach and Meehl (1955), though updated framings of this idea (Campbell & Fiske, 1959; Messick, 1995) are likely to be more useful. It is expected that the benefits of nomological networks will be dramatically improved with more circumscribed boundaries, not only with respect to their traditional use in making claims about construct validation but more importantly in the empirical testing of theories that are qualitatively distinct from those that have previously been common in personality psychology. In other words, the advancement of *strong* theories that “explicate a precise set of assumptions and axioms about a phenomenon non-ambiguously” (p. 4, Fried, 2020), rather than the more familiar class of *weak* theories in psychology that merely specify relations among variables and are effectively incapable of being disconfirmed.

Towards a digital representation of the analog experience

In our view, an important but imperceptible fracture has developed in personality science: that the aims of personality science research are increasingly less aligned with the goals of person-level personality assessment. The basis for this fracture has likely been present for decades, as the aims of basic personality research have consistently differed from the aims of personality testing. Realization of the fracture, however, has occurred as the potential to capture much more informative and diverse data has increased over time. The demands of testing – scalability across test-takers, efficiency in administration and interpretation, and utility for each individual – encourage a myopically nomothetic, conservative, and opaque approach to assessment. By contrast, research would often benefit from assessment techniques that are more flexible, inclusive, and transparent.

The person perception literature provides a ready example of this situation because it is evident that the Big Five is a poor match for the analog experience of assessing the personality of

INFORMATION THEORY IN PERSONALITY

others, so we shall revisit the analog/digital distinction as we conclude. This sub-discipline of personality science has generally invoked broad operationalizations of personality when exploring the procedural components of personality judgment. Mainly, this has meant the use of traits like the Big Five, even when considering judgments of very narrow behaviors that are typically briefly expressed, and studied with stimuli like photographs (Borkenau, Brecke, Möttig, & Paelecke, 2009; Gosling, Ko, Mannarelli, & Morris, 2002). This need not be the default, for the ever-increasing bandwidth of data collection provides an opportunity for researchers to more fully capture the rich complexity of psychological individual differences. Yet, this cannot be achieved without some detailed alternative framework (Condon et al., 2020). With concerted effort and time, the personality assessment sub-field can make this happen. It requires the development of personality assessment tools – based on information-theoretic aims rather than data reduction via latent variable models – that invoke much more complex framing of personality than is necessary for psychological testing applications. Consider, for example, the benefit gained from an understanding of the relation between accuracy of judgments for smiling behavior as a function of “Extraversion” vs “variance in emotional expressiveness using items X, Y, and Z across situations involving 3 or more non-familial others.” The former allows for much less formal theory testing and refinement than the latter.

Our call for information-theoretic approaches is not intended as a reversal of Cronbach’s dismissal. We acknowledge that tremendous benefit has come from the identification of broad, omnibus assessment tools, and that there will continue to be many use cases where these remain the best recommendation. We further acknowledge that the steps we have outlined herein require substantial field-wide investment beyond the scope of what can be achieved by individual research teams. Yet, the time is ripe for looking beyond the broad and intentionally under-informed methods of assessment that are predominantly used by researchers today. Our aspiration for personality assessment is to begin assembling an alternative to these dominant tools that can digitally reproduce the complex and diverse analog experience of personality in everyday life.

References

- Aborn, M., and Rubenstein, H. (1952). Information theory and immediate recall. *Journal of Experimental Psychology*, 44, 260-266. <https://doi.org/10.1037/h0061660>
- Aldrich, J. (1997). R.A. Fisher and the making of maximum likelihood 1912-1922. *Statistical Science*, 12(3), 162-176. <https://doi.org/10.1214/ss/1030037906>
- Allport, G. W. (1928). A test for ascendance-submission. *The Journal of Abnormal and Social Psychology*, 23(2), 118. <https://doi.org/10.1037/h0074218>
- Allport, G. W., & Odbert, H. S. (1936). Trait-names: A psycho-lexical study. *Psychological Monographs: General and Applied*, 47(1), 1-170. <https://doi.org/10.1037/h0093360>
- Anastasi, A. (1950). The concept of validity in the interpretation of test scores. *Educational and Psychological Measurement*, 10(1), 67-78. <https://doi.org/10.1177/001316445001000105>
- Armstrong, P. I., Allison, W., & Rounds, J. (2008). Development and initial validation of brief public domain RIASEC marker scales. *Journal of Vocational Behavior*, 73(2), 287-299. <https://doi.org/10.1016/j.jvb.2008.06.003>
- Ashton, M. C., Lee, K., & Goldberg, L. R. (2004). A hierarchical analysis of 1,710 English personality-descriptive adjectives. *Journal of Personality and Social Psychology*, 87(5):707.1 <https://doi.org/10.1037/0022-3514.87.5.707>
- Attneave, F. (1959). *Applications of Information theory to Psychology: A Summary of Basic Concepts, Methods, and Results*. New York, NY: Henry Holt.
- Bernreuter, R. G. (1931). *The personality inventory*. Stanford University Press. <https://doi.org/10.1037/t02035-000>
- Bernreuter, R. G. (1933). The theory and construction of the personality inventory. *The Journal of Social Psychology*, 4(4), 387-405. <https://doi.org/10.1080/00224545.1933.9919335>
- Borkenau, P., Brecke, S., Möttig, C., & Paelecke, M. (2009). Extraversion is accurately perceived after a 50-ms exposure to a face. *Journal of Research in Personality*, 43(4), 703-706. <https://doi.org/10.1016/j.jrp.2009.03.007>
- Borsboom, D. (2008) Latent Variable Theory. *Measurement*, 6:1-2, 25-53. <https://doi.org/10.1080/15366360802035497>
- Broadbent, D. E. (1957). A mechanical model for human attention and immediate memory. *Psychological review*, 64(3), 205. <https://doi.org/10.1037/h0047313>
- Brunswik, E. (1952). The conceptual framework of psychology. *International Encyclopedia of Unified Science*, Volume 1, Number 10. Chicago: The University of Chicago Press.

INFORMATION THEORY IN PERSONALITY

- Brunswik, E. (1955). Representative design and probabilistic theory in a functional psychology. *Psychological Review*, 62(3), 193. <https://doi.org/10.1037/h0047470>
- Campbell, D. T. (1958). Systematic error on the part of human links in communication systems. *Information and Control*, 1(4), 334-369. [https://doi.org/10.1016/S0019-9958\(58\)90219-5](https://doi.org/10.1016/S0019-9958(58)90219-5)
- Campbell, D. T., & Fiske, D. W. (1959). Convergent and discriminant validation by the multitrait-multimethod matrix. *Psychological Bulletin*, 56(2), 81. <https://doi.org/10.1037/h0046016>
- Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge, UK: Cambridge University Press. <https://doi.org/10.1017/CBO9780511571312>
- Cattell, R. B. (1946). *Description and measurement of personality*. Oxford, England: World Book Company.
- Cattell, R.B. (1946). Personality structure and measurement. I. The operational determination of trait unities. *British Journal of Psychology*, 36, 88-102. <https://doi.org/10.1111/j.2044-8295.1946.tb01110.x>
- Cattell, R. B. (1947). Confirmation and clarification of primary personality factors. *Psychometrika*, 12(3), 197-220. <https://doi.org/10.1007/BF02289253>
- Cattell RB. (1966). The data box: its ordering of total resources in terms of possible relational systems. In Cattell R. B. (Ed.), *Handbook of multivariate experimental psychology*. pp. 67-128. Chicago, IL: Rand McNally.
- Cattell, R. B. (1987). *Intelligence: Its structure, growth and action*. New York: North Holland.
- Condon, D. M. (2014). *An organizational framework for the psychological individual differences: Integrating the affective, cognitive, and conative domains*. PhD thesis, Northwestern University, Evanston, IL. <https://doi.org/10.31237/osf.io/7uj8z>
- Condon, D. (2019). *Database of Individual Differences Survey Tools*. Harvard Dataverse. doi:10.7910/DVN/T1NQ4V
- Condon, D. M., Chapman, R., Shaunfield, S., Kallen, M. A., Beaumont, J. L., Eek, D., ... & Shaw, J. W. (2020). Does recall period matter? Comparing PROMIS® physical function with no recall, 24-hr recall, and 7-day recall. *Quality of Life Research*, 29(3), 745-753. <https://doi.org/10.1007/s11136-019-02344-0>
- Condon, D. M., Wood, D., Möttus, R., Booth, T., Costantini, G., Greiff, S., Johnson, W., Lukaszewski, A., Murray, A., Revelle, W., Wright, A. G. C., Ziegler, M., & Zimmermann, J. (2020). Bottom Up Construction of a Personality Taxonomy. *European Journal of Psychological Assessment*, 36(6), 923-934. <https://doi.org/10.1027/1015-5759/a000626>

INFORMATION THEORY IN PERSONALITY

- Cooksey, R.W. (2001). Brunswik's The Conceptual Framework of Psychology: Then and Now. In K. R. Hammond and T. R. Stewart (Eds.), *The Essential Brunswik: Beginnings, Explanations, Applications* (pages 225-237 of chapter 12). Oxford University Press.
- Cooper, A. B., Blake, A. B., Pauletti, R. E., Cooper, P. J., Sherman, R. A., & Lee, D. I. (2020). Personality Assessment Through the Situational and Behavioral Features of Instagram Photos. *European Journal of Psychological Assessment*. <https://doi.org/10.1027/1015-5759/a000596>
- Cronbach, L. J. (1947). Test "reliability": Its meaning and determination. *Psychometrika*, 12(1), 1-16. <https://doi.org/10.1007/BF02289289>
- Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika*, 16(3), 297-334. <https://doi.org/10.1007/BF02310555>
- Cronbach, L. J. (1952). *A generalized psychometric theory based on information theory*. Urbana, Illinois: Bureau of Research; Service, College of Education, University of Illinois.
- Cronbach, L. J. (1953). *A consideration of information theory and utility theory as tools for psychometric problems* (No. 1). Office of Naval Research.
- Cronbach, L. J. (1955a). On the non-rational application of information measures in psychology. In H. Quastler (Ed.), *Information theory in psychology* (pp. 14-26). Glencoe, Illinois: The Free Press.
- Cronbach, L. J. (1955b). Processes affecting scores on "understanding of others" and "assumed similarity." *Psychological Bulletin*, 52(3), 177. <https://doi.org/10.1037/h0044919>
- Cronbach, L. J. (1960). *Essentials of psychological testing* (2nd ed.). New York, NY: Harper & Brothers.
- Cronbach, L. J. (1970). Mental tests and the creation of opportunity. *Proceedings of the American Philosophical Society*, 114(6), 480-487.
- Cronbach, L. J., & Gleser, G. C. (1964). The signal/noise ratio in the comparison of reliability coefficients. *Educational and Psychological Measurement*, 24(3), 467-480. <https://doi.org/10.1177/001316446402400303>
- Cronbach, L. J., & Gleser, G. C. (1965). *Psychological tests and personnel decisions* (2nd ed.). Urbana, Illinois: University of Illinois Press.
- Cronbach, L. J., & Meehl, P. E. (1955). Construct validity in psychological tests. *Psychological bulletin*, 52(4), 281. <https://doi.org/10.1037/h0040957>
- Deary, I. J., & Bedford, A. (2011). Some origins and evolution of the epq-r (short form) neuroticism and extraversion items. *Personality and Individual Differences*, 50(8), 1213-1217. <https://doi.org/10.1016/j.paid.2011.02.011>
- Del Giudice, M. (2020). Effective Dimensionality: A Tutorial. *Multivariate Behavioral Research*, 1-16. <https://doi.org/10.1080/00273171.2020.1743631>

INFORMATION THEORY IN PERSONALITY

- Edwards, K., & Von Hippel, W. (1995). Hearts and minds: The priority of affective versus cognitive factors in person perception. *Personality and Social Psychology Bulletin*, 21(10), 996-1011. <https://doi.org/10.1177/01461672952110001>
- Fisher, R. A. (1922). On the mathematical foundations of theoretical statistics. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, 222(594-604), 309-368. <https://doi.org/10.1098/rsta.1922.0009>
- Fleeson, W. (2004). Moving personality beyond the person-situation debate: The challenge and the opportunity of within-person variability. *Current Directions in Psychological Science*, 13(2), 83-87. <https://doi.org/10.1111/j.0963-7214.2004.00280.x>
- Fried, E. I. (2020). Lack of theory building and testing impedes progress in the factor and network literature. *PsyArXiv*. <https://doi.org/10.31234/osf.io/zg84s>
- Freyd, M. (1924). Introverts and extroverts. *Psychological Review*, 31(1), 74. <https://doi.org/10.1037/h0075875>
- Funder, D. C. (1995). On the Accuracy of Personality Judgment: A Realistic Approach. *Psychological Review*, 102(4), 652-670. <https://doi.org/10.1037/0033-295X.102.4.652>
- Funder, D. C. (2006). Towards a resolution of the personality triad: Persons, situations, and behaviors. *Journal of Research in Personality*, 40(1), 21-34. <https://doi.org/10.1016/j.jrp.2005.08.003>
- Funder, D. C., & West, S. G. (1993). Consensus, self-other agreement, and accuracy in personality judgment: An introduction. *Journal of Personality*, 61(4), 457-476. <https://doi.org/10.1111/j.1467-6494.1993.tb00778.x>
- Galton, F. (1884). The measurement of character. *Fortnightly Review*, 42, 179-185.
- Gage, N. L., & Cronbach, L. J. (1955). Conceptual and methodological problems in interpersonal perception. *Psychological Review*, 62(6), 411. <https://doi.org/10.1037/h0047205>
- Gibby, R. E., & Zickar, M. J. (2008). A history of the early days of personality testing in american industry: An obsession with adjustment. *History of Psychology*, 11(3), 164. <https://doi.org/10.1037/a0013041>
- Girard, J. M., & Cohn, J. F. (2016). A primer on observational measurement. *Assessment*, 23(4), 404-413. <https://doi.org/10.1177/1073191116635807>
- Goldberg, L. R. (1971). A historical survey of personality scales and inventories. In P. McReynolds (Ed.), *Advances in psychological assessment* (Vol. 2). Science; Behavior Books.
- Goldberg, L. R. (1990). An alternative "description of personality": The Big-Five factor structure. *Journal of Personality and Social Psychology*, 59(6), 1216-1229. <https://doi.org/10.1037/0022-3514.59.6.1216>

INFORMATION THEORY IN PERSONALITY

- Goldberg, L. R. (1992). The development of markers for the Big-Five factor structure. *Psychological assessment*, 4(1), 26. <https://doi.org/10.1037/1040-3590.4.1.26>
- Goldberg, L. R. (1993a). The structure of personality traits: Vertical and horizontal. In D. C. Funder, R. D. Parke, C. Tomlinson-Keasey, & K. Widaman (Eds.), *Studying lives through time: Personality and development* (pp. 169-188). Washington, DC: American Psychological Association.
- Goldberg, L. R. (1993b). The structure of phenotypic personality traits. *American Psychologist*, 48, 26-34. <https://doi.org/10.1037/0003-066X.48.1.26>
- Goldberg, L. R. (1999). A broad-bandwidth, public domain, personality inventory measuring the lower-level facets of several Five-Factor Models. In Mervielde, I., Deary, I., De Fruyt, F., and Ostendorf, F. (editors), *Personality and Individual Differences*, pages 7-28. Tilburg University Press, The Netherlands.
- Goldberg, L. R., & Saucier, G. (2016). *The Eugene-Springfield Community Sample: Information Available from the Research Participants* (No. 1) (Vol. 56). Oregon Research Institute.
- Golino, H., Moulder, R., Shi, D., Christensen, A. P., Garrido, L. E., Nieto, M. D., Nesselroade, J., Sadana, R., Thiagarajan, J. A., & Boker, S. M. (2020). Entropy Fit Indices: New Fit Measures for Assessing the Structure and Dimensionality of Multiple Latent Variables. *Multivariate Behavioral Research*, 1-29. <https://doi.org/10.1080/00273171.2020.1779642>
- Gosling, S. D., Ko, S. J., Mannarelli, T., & Morris, M. E. (2002). A room with a cue: Personality judgments based on offices and bedrooms. *Journal of Personality and Social Psychology*, 82(3), 379. <https://doi.org/10.1037/0022-3514.82.3.379>
- Gosling, S. D., Rentfrow, P. J., & Swann Jr, W. B. (2003). A very brief measure of the Big-Five personality domains. *Journal of Research in Personality*, 37(6), 504-528. [https://doi.org/10.1016/S0092-6566\(03\)00046-1](https://doi.org/10.1016/S0092-6566(03)00046-1)
- Hall, A. N., & Matz, S. C. (2020.). Targeting Item-level Nuances Leads to Small but Robust Improvements in Personality Prediction from Digital Footprints. *European Journal of Personality*. <https://doi.org/10.1002/per.2253> <https://doi.org/10.1002/per.2253>
- Harari, G. M., Müller, S. R., Aung, M. S., & Rentfrow, P. J. (2017). Smartphone sensing methods for studying behavior in everyday life. *Current Opinion in Behavioral Sciences*, 18, 83-90. <https://doi.org/10.1016/j.cobeha.2017.07.018>
- Harari, G. M., Vaid, S. S., Müller, S. R., Stachl, C., Marrero, Z., Schoedel, R., Bühner, M., & Gosling, S. D. (2020). Personality Sensing for Theory Development and Assessment in the Digital Age. *European Journal of Personality*. <https://doi.org/10.1002/per.2273>
- Holland, J. L. (1959). A theory of vocational choice. *Journal of Counseling Psychology*, 6(1), 35. <https://doi.org/10.1037/h0040767>

INFORMATION THEORY IN PERSONALITY

- Hogan, J., & Roberts, B. W. (1996). Issues and non-issues in the fidelity-bandwidth trade-off. *Journal of Organizational Behavior*, 17(6), 627-637. [https://doi.org/10.1002/\(SICI\)1099-1379\(199611\)17:6<627::AID-JOB2828>3.0.CO;2-F](https://doi.org/10.1002/(SICI)1099-1379(199611)17:6<627::AID-JOB2828>3.0.CO;2-F)
- House, S. D. (1927). A mental hygiene inventory. *Archives of Psychology*, 14(88), 112.
- Jackson, D. N., & Paunonen, S. V. (1980). Personality structure and assessment. *Annual review of psychology*, 31(1), 503-551. <https://doi.org/10.1146/annurev.ps.31.020180.002443>
- John, O. P., & Srivastava, S. (1999). The Big Five trait taxonomy: History, measurement, and theoretical perspectives. In Pervin, L. A., & John, O. P. (Eds.), *Handbook of personality: Theory and research*, 102-138.
- Johnson, J. A. (2014). Measuring thirty facets of the Five Factor Model with a 120-item public domain inventory: Development of the IPIP-NEO-120. *Journal of Research in Personality*, 51, 78-89. <https://doi.org/10.1016/j.jrp.2014.05.003>
- Jones, A. B., Brown, N. A., Serfass, D. G., & Sherman, R. A. (2017). Personality and density distributions of behavior, emotions, and situations. *Journal of Research in Personality*, 69, 225-236. <https://doi.org/10.1016/j.jrp.2016.10.006>
- Jung, C. (2016). *Psychological types*. Taylor & Francis. <https://doi.org/10.4324/9781315512334>
- Kopp C., Korb K. B., & Mills, B. I. (2018). Information-theoretic models of deception: Modelling cooperation and diffusion in populations exposed to "fake news". *PLoS ONE* 13(11): e0207383. <https://doi.org/10.1371/journal.pone.0207383>
- Laird, D. (1925). *General information and directions for using the Colgate tests of emotional outlets*. Hamilton: Hamilton Republican.
- Leary, D. E. (1987). From Act Psychology to Problematic Functionalism: The Place of Egon Brunswik in the History of Psychology. In Ash, M. G. and Woodward, W. R. (Eds). *Psychology in Twentieth-Century Thought and Society*. pages 115-42. Cambridge: Cambridge University Press.
- Letzring, T. D., Wells, S. M., & Funder, D. C. (2006). Information quantity and quality affect the realistic accuracy of personality judgment. *Journal of personality and social psychology*, 91(1), 111. <https://doi.org/10.1037/0022-3514.91.1.111>
- Lord, F. M. (1953). The relation of test score to the trait underlying the test. *Educational and Psychological Measurement*, 13(4), 517-549. <https://doi.org/10.1177/001316445301300401>
- Markon, K. E. (2013). Information utility: Quantifying the total psychometric information provided by a measure. *Psychological Methods*, 18(1), 15. <https://doi.org/10.1037/a0030638>

INFORMATION THEORY IN PERSONALITY

- Mulaik, S. A. (1987). A brief history of the philosophical foundations of exploratory factor analysis. *Multivariate Behavioral Research*, 22(3), 267-305. https://doi.org/10.1207/s15327906mbr2203_3
- McAdams, D., & Pals, J. (2006). A new Big Five: Fundamental principles for an integrative science of personality. *American Psychologist*, 61(3), 204-217. <https://doi.org/10.1037/0003-066X.61.3.204>
- McCrae, R. R. (2015). A more nuanced view of reliability: Specificity in the trait hierarchy. *Personality and Social Psychology Review*, 19(2), 97-112. <https://doi.org/10.1177/1088868314541857>
- Meehl, P. E. (1954). *Clinical versus statistical prediction: A theoretical analysis and a review of the evidence*. University of Minnesota Press. <https://doi.org/10.1037/11281-000>
- Messick, S. (1995). Validity of psychological assessment: Validation of inferences from persons' responses and performances as scientific inquiry into score meaning. *American Psychologist*, 50(9), 741. <https://doi.org/10.1037/0003-066X.50.9.741>
- Meyer, L. B. (1957). Meaning in music and information theory. *Journal of Aesthetics and Art Criticism*, 15, 412-424. <https://doi.org/10.2307/427154>
- Miller, G. A. (2003). The cognitive revolution: a historical perspective. *Trends in Cognitive Science*, 7, 141-144. [https://doi.org/10.1016/S1364-6613\(03\)00029-9](https://doi.org/10.1016/S1364-6613(03)00029-9)
- Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, 63, 81-97. <https://doi.org/10.1037/h0043158>
- Möttus, R., Wood, D., Condon, D. M., Back, M., Baumert, A., Costantini, G., Epskamp, S., Greiff, S., Johnson, W., Lukaszewski, A., Murray, A., Revelle, W., Wright, A. G. C., Yarkoni, T., Ziegler, M., & Zimmermann, J. (2020). Descriptive, predictive and explanatory personality research: Different goals, different approaches, but a shared need to move beyond the Big Few traits. *European Journal of Personality*, 34(6), 1175-1201. <https://doi.org/10.1002/per.2311>
- Nicewander, W. A. (1993). Some relationships between the information function of IRT and the signal/noise ratio and reliability coefficient of classical test theory. *Psychometrika*, 58(1), 139-141. <https://doi.org/10.1007/BF02294477>
- Norman, W. T. (1963). Toward an adequate taxonomy of personality attributes: Replicated factor structure in peer nomination personality ratings. *Journal of Abnormal and Social Psychology*, 66(6), 574-583. <https://doi.org/10.1037/h0040291>
- Norman, W. T. (1967). *2800 personality trait descriptors: Normative operating characteristics for a university population*. Ann Arbor: Department of Psychology, University of Michigan.
- Ones, D. S., & Viswesvaran, C. (1996). Bandwidth-fidelity dilemma in personality measurement for personnel selection. *Journal of Organizational Behavior*, 17(6), 609-626. [https://doi.org/10.1002/\(SICI\)1099-1379\(199611\)17:6<609::AID-JOB1828>3.0.CO;2-K](https://doi.org/10.1002/(SICI)1099-1379(199611)17:6<609::AID-JOB1828>3.0.CO;2-K)

INFORMATION THEORY IN PERSONALITY

- Poffenberger, A. T. (1962). Robert Sessions Woodworth: 1869-1962. *The American Journal of Psychology*, 75, 677-689.
- Prediger, D. J. (1982). Dimensions underlying Holland's hexagon: Missing link between interests and occupations? *Journal of Vocational Behavior*, 21(3), 259-287. [https://doi.org/10.1016/0001-8791\(82\)90036-7](https://doi.org/10.1016/0001-8791(82)90036-7)
- Quastler, H. (Ed.). (1955). *Information theory in psychology* (pp. 14-26). Glencoe, Illinois: The Free Press.
- Rammstedt, B., & John, O. P. (2007). Measuring personality in one minute or less: A 10-item short version of the Big Five Inventory in English and German. *Journal of Research in Personality*, 41(1), 203-212. <https://doi.org/10.1016/j.jrp.2006.02.001>
- Rauthmann, J. F., Gallardo-Pujol, D., Guillaume, E. M., Todd, E., Nave, C. S., Sherman, R. A., Ziegler, M. A., Jones, A. B., & Funder, D. C. (2014). The situational eight DIAMONDS: A taxonomy of major dimensions of situation characteristics. *Journal of Personality and Social Psychology*, 107(4), 677. <https://doi.org/10.1037/a0037250>
- Reischer, H. N., & Cowan, H. R. (2020). Quantity Over Quality? Reproducible Psychological Science from a Mixed Methods Perspective. *Collabra: Psychology*, 6(1). <https://doi.org/10.1525/collabra.284>
- Revelle, W., Condon, D. M., Wilt, J. A., French, J. A., Brown, A. D., & Elleman, L. G. (2016). Web and phone based data collection using planned missing designs. In N. G. Fielding, R. M. Lee, & G. Blank (Eds.), *Handbook of online research methods*. Thousand Oaks, CA. <https://doi.org/10.4135/9781473957992.n33>
- Revelle, W., & Condon, D. M. (2019). Reliability from α to ω : A tutorial. *Psychological Assessment*, 31(12), 1395. <https://doi.org/10.1037/pas0000754>
- Revelle, W., Wilt, J., & Condon, D. M. (2011). Individual differences and differential psychology: A brief history and prospect. In T. Chamorro-Premuzic, S. von Stumm, & A. Furnham (Eds.), *The Wiley-Blackwell Handbook of Individual Differences* (pp. 3-38). Oxford: Wiley-Blackwell.
- Rioul, O. (2018). This is IT: A primer on Shannon's entropy and information. *Séminaire Poincaré*, 23, 43-77.
- Roberts, B. W., Lejuez, C., Krueger, R. F., Richards, J. M., & Hill, P. L. (2014). What is conscientiousness and how can it be assessed?. *Developmental psychology*, 50(5), 1315. <https://doi.org/10.1037/a0031109>
- Rodgers, L. J., & Nicewander, W. A. (1988). Thirteen ways to look at the correlation coefficient. *The American Statistician*, 42(1), 59-66. <https://doi.org/10.2307/2685263>
- Saucier, G. (1997). Effects of variable selection on the factor structure of person descriptors. *Journal of Personality and Social Psychology*, 73(6), 1296. <https://doi.org/10.1037/0022-3514.73.6.1296>

INFORMATION THEORY IN PERSONALITY

- Shannon, C. E. (1948a). A mathematical theory of communication (Part 1). *The Bell System Technical Journal*, 27(3), 379-423. <https://doi.org/10.1002/j.1538-7305.1948.tb01338.x>
- Shannon, C. E. (1948b). A mathematical theory of communication (Part 2). *The Bell System Technical Journal*, 27(4), 623-656. <https://doi.org/10.1002/j.1538-7305.1948.tb00917.x>
- Shannon, C. E. (1956). The bandwagon. *IRE Transactions on Information Theory*, 2(1), 3. <https://doi.org/10.1109/TIT.1956.1056774>
- Smaldino, P. E., Flamson, T. J., & McElreath, R. (2018). The evolution of covert signaling. *Scientific Reports*, 8(1), 1-10. <https://doi.org/10.1038/s41598-018-22926-1>
- Spearman C. (1904a). The proof and measurement of association between two things. *American Journal of Psychology*, 15(1): 72-101. <https://doi.org/10.2307/1412159>
- Spearman, C. (1904b). "General intelligence," objectively determined and measured. *American Journal of Psychology*, 15, 201-292. <https://doi.org/10.2307/1412107>
- Stachl, C., Au, Q., Schoedel, R., Gosling, S. D., Harari, G. M., Buschek, D., Völkel, S. T., Schuwerk, T., Oldemeier, M., Ullmann, T., Hussmann, H., Bischl, B., & Bühner, M. (2020). Predicting personality from patterns of behavior collected with smartphones. *Proceedings of the National Academy of Sciences*, 117, 17680-17687. <https://doi.org/10.1073/pnas.1920484117>
- Tay, L., Woo, S. E., Hickman, L., & Saef, R. M. (2020). Psychometric and Validity Issues in Machine Learning Approaches to Personality Assessment: A Focus on Social Media Text Mining. *European Journal of Personality*. <https://doi.org/10.1002/per.2290>
- Thurstone, L. L., & Thurstone, T. G. (1930). A neurotic inventory. *The Journal of Social Psychology*, 1(1), 3-30. <https://doi.org/10.1080/00224545.1930.9714128>
- Thurstone, L. L. (1931). Multiple factor analysis. *Psychological review*, 38(5), 406. <https://doi.org/10.1037/h0069792>
- Todorov, A., Olivola, C. Y., Dotsch, R., & Mende-Siedlecki, P. (2015). Social attributions from faces: Determinants, consequences, accuracy, and functional significance. *Annual Review of Psychology*, 66, 519-545. <https://doi.org/10.1146/annurev-psych-113011-143831>
- Uher, J. (2013). Personality psychology: Lexical approaches, assessment methods, and trait concepts reveal only half of the story-Why it is time for a paradigm shift. *Integrative Psychological and Behavioral Science*, 47(1), 1-55. <https://doi.org/10.1007/s12124-013-9230-6>
- Wang, F., & De Filippi, P. (2020). Self-sovereign identity in a globalized world: Credentials-based identity systems as a driver for economic inclusion. *Frontiers in Blockchain*, 2, 28. <https://doi.org/10.3389/fbloc.2019.00028>
- Whyte, W. H. (1956). *The organization man*. 1956. New York, NY: Simon; Schuster.

INFORMATION THEORY IN PERSONALITY

- Wiernik, B. M., Ones, D. S., Marlin, B. M., Giordano, C., Dilchert, S., Mercado, B. K., Stanek, K. C., Birkland, A., Wang, Y., Ellis, B., Yazar, Y., Kostal, J. W., Kumar, S., Hnat, T., Ertin, E., Sano, A., Ganesan, D. K., Choudhury, T., & al'Absi, M. (2020). Using Mobile Sensors to Study Personality Dynamics. *European Journal of Psychological Assessment*.
<https://doi.org/10.1027/1015-5759/a000576>
- Woodworth, R. S. (1917). *Personal data sheet*. Chicago, IL: Stoelting.
- Xiong, A., & Proctor, R. W. (2018). Information processing: The language and analytical tools for cognitive psychology in the information age. *Frontiers in psychology*, 9, 1270.
<https://doi.org/10.3389/fpsyg.2018.01270>