A Strong Interactive Link between Sensory Discriminations and Intelligence

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Summary

Early psychologists, including Galton, Cattell, and Spearman, proposed that intelligence and simple sensory discriminations are constrained by common neural processes, predicting a close link between them [1, 2]. However, strong supporting evidence for this hypothesis remains elusive. Although people with higher intelligence quotients (IQs) are quicker at processing sensory stimuli [1–5], these broadly replicated findings explain a relatively modest proportion of variance in IQ. Processing speed alone is, arguably, a poor match for the information processing demands on the neural system. Our brains operate on overwhelming amounts of information [6, 7], and thus their efficiency is fundamentally constrained by an ability to suppress irrelevant information [8–21]. Here, we show that individual variability in a simple visual discrimination task that reflects both processing speed and perceptual suppression [22] strongly correlates with IQ. High-IQ individuals, although quick at perceiving small moving objects, exhibit disproportionately large impairments in perceiving motion as stimulus size increases. These findings link intelligence with low-level sensory suppression of large moving patterns—background-like stimuli that are ecologically less relevant [22–25]. We conjecture that the ability to suppress irrelevant and rapidly process relevant information fundamentally constrains both sensory discriminations and intelligence, providing an information-processing basis for the observed link.

Results

Motivated by fundamental roles of suppressive processes in neural function [8–21], we hypothesized that individual differences in a low-level visual task that reflects both processing speed and perceptual suppression should closely correlate with intelligence quotient (IQ). To estimate perceptual suppression, we used a simple visual task in which subjects identified motion direction of briefly presented grating stimuli [22] (Figure 1A; see also Supplemental Experimental Procedures available online). We adaptively adjusted stimulus duration to estimate the shortest exposure durations sufficient for threshold-level performance. This approach is analogous to conventional inspection time measures [2–4] and provides an estimate of perceptual processing speed. The critical manipulation was stimulus size (Figure 1B). We previously found that as stimulus size increases, motion direction of high-contrast patterns becomes markedly harder to perceive [22] (Figure 1C). This counterintuitive result, termed spatial suppression, is believed to reflect inhibitory mechanisms that render motion-selective neurons less responsive to large, background-like motion patterns, stimuli that are less likely to be perceptually relevant [22–28]. Importantly, subjects were not asked to suppress or ignore large moving stimuli; rather, they were instructed to identify motion direction of each individually presented stimulus as accurately as possible. To quantify the strength of spatial suppression, we computed suppression index (SI) (Figure 1C), simply defined as the difference between the threshold for large stimuli and the threshold for small stimuli [27–30] (Figure 1C). Thus, SI indexes the degree of impairment in motion perception with increasing stimulus size.

Next, we examined the relationship between SI and WAIS-IV index scores (study 2). Sensory measures tend to be better...
Speed Indices were r = 0.69, 0.47, 0.49, and 0.50, respectively. Perceptual Reasoning, Working Memory, and Processing contrast, SI is a good predictor of broad intellectual ability: SI is strongly linked with a broad range of psychometric measures of general intellectual ability. Overall, we show that SI is strongly linked with a broad range of psychometric indices of intelligence.

What drives the SI-IQ relationship? SI indexes the difference between one’s ability to perceive small and large moving stimuli (Figure 1C). Thus, the observed relationship indicates an interactive link between motion perception and IQ. Indeed, correlations between IQ and subjects’ ability to perceive motion of small and large stimuli were significantly different (Figures 3A and 3B; both z > 2.0, p < 0.04). As IQ rises, SI increases because of (1) faster processing of small stimuli coupled with (2) a diminishing ability to perceive large moving stimuli. Neither effect alone was sufficient to account for the observed SI-IQ link; only small-stimulus thresholds in study 2 significantly correlated with IQ (r = −0.46, p = 0.0005), indicating that performance with large stimuli is a key component of the SI-IQ link. Thus, we considered factors that may affect the correlation between IQ and large-stimulus thresholds. The ability to perceive large moving stimuli is determined both by spatial suppression [22] and by nonspecific factors (e.g., general motion sensitivity and motivation). Such general factors tend to be positively correlated with IQ [3, 34], but they should affect motion perception regardless of stimulus size, allowing us to statistically control for nonspecific effects. First, to control for the shared variance between subjects’ performance with small and large stimuli, we computed semipartial correlations between stimulus thresholds and IQ (study 2). The results revealed significant but opposite correlations between IQ and small-stimulus (Figure 3C; sr = −0.71, p = 10−8) and large-stimulus (Figure 3D; sr = 0.55, p = 10−5) thresholds. These results were further supported by a multiple linear regression analysis with thresholds for small and large stimuli as predictors of IQ scores (R² = 0.52, F₂,₅₀ = 26.7, p = 10−8, variance inflation factor < 1.7). High IQ was associated with lower thresholds for small moving stimuli (β = −0.92, t₅₀ = −7.2, p = 10−8) and higher thresholds for large moving stimuli (β = 0.72, t₅₀ = 5.6, p = 10−5). We found analogous results for the four WAIS-IV index scores (all R² > 0.23, F₂,₅₀ > 7.55, p < 0.001), where high IQ was predicted by lower small-stimulus thresholds (−0.89 < β < −0.58; all p < 0.006) and higher large-stimulus thresholds (0.68 > β > 0.41; all p < 0.011). In conclusion, rather than being linked with an overall speeding of motion perception, we found that high IQ is associated...
showed that as stimulus size increased, thresholds decreased under a regime largely unaffected by suppressive processes. The results (Figure 4A) favored smaller moving stimuli relative to large.

Lastly, we examined whether the observed link between motion perception and IQ is specific to suppressive processes or extends to other motion phenomena that change with increasing size. Spatial suppression is restricted to middle and high contrasts. As stimulus contrast decreases, spatial tuning of motion perception gradually shifts from spatial summation [22], which is manifested as improved discriminability of low-contrast motions with increasing size. Spatial suppression is restricted to middle or extends to other motion phenomena that change with increasing size. Thus, by simply reducing stimulus contrast, we can measure perceptual discriminations without a regime largely unaffected by suppressive processes. Such low-contrast stimuli were tested in study 1 (2.8% hold contrasts).

Our findings endorse Sir Francis Galton and Charles Spearman’s original hypotheses [1] and reveal a close empirical link between sensory discriminations and intelligence. Since the early days of intelligence research, psychologists have hypothesized that sensory discriminations and intelligence are constrained by common underlying mechanisms [1, 2]. The proposed sensory correlates held promise of providing nonverbal, culture-fair measures of intelligence within a biologically constrained theoretical framework. Indeed, it is well established that IQ scores correlate with measures of inspection time: high-IQ subjects require shorter stimulus exposure times to make simple perceptual judgments [1–5]. Similar results were found using reaction time measures [1–4]. These findings are intuitive—rapid information processing is important for both sensory discriminations and intelligence. However, the reported links were modest, with uncorrected correlations typically between 0.2 and 0.4 [2–4]. Still, there are indications that the underlying relationship between sensory discriminations and IQ is likely stronger than suggested by bivariate correlations. Structural equation modeling has revealed remarkably strong links (0.68 ≤ r ≤ 0.92) between two latent traits: general intelligence and general sensory discrimination [37, 38]. Moreover, basic sensory processing has been shown to account for intelligence variations in old age, suggesting that a common cause might underlie both cognitive and sensory declines in senescence [39].

Why do our results exceed previously documented empirical links between IQ and sensory discriminations? By using time-limited stimuli, our approach incorporates the key feature found in studies that show the most consistent empirical links between IQ and sensory tasks [5]. Our results, however, show that while processing speed is indeed related to IQ, it alone is insufficient to account for the SI-IQ link. Rather, it is the relative inability to quickly perceive large moving stimuli (i.e., SI) that predicts variations in IQ scores. This finding supports the argument that rapid processing is of limited utility unless it is restricted to the most relevant information. This is critical for any system that operates on information that exceeds its processing capacity—a description that characterizes both perception and intelligence and suggests a possible information-processing basis for the observed relationship. However, while information relevance in the context of intelligent cognition changes depending on task demands, the implicit assumption behind our perceptual results is that the relevance of different sizes of moving stimuli is predetermined. This
assumption has ecological validity, given that large moving stimuli are more likely to come from typically less relevant background motion [40]. Moreover, the insensitivity to background motion is built into responses of motion-selective neurons as center-surround suppression [23]. A key exception occurs at low-contrast levels, where weakening of suppression is exhibited by both neural center-surround mechanisms [41] and behavioral motion sensitivity [22]. Paralleling this weakening of spatial suppression, we did not find a link between SI and IQ at low contrast (Figure 4).

While our results are the first report linking sensory suppression and intelligence, the central importance of inhibition in cognitive processing is well established [12–19, 42]. Working-memory performance is predicted not by neural enhancement of task-relevant information but rather by individual differences in neural suppression of distractors [12, 13]. The ability to ignore highly distracting items in working memory predicts individual differences in intelligence [16] and can account for differences in prefrontal cortex activity between low- and high-IQ individuals [16, 17]. Our results, while consistent with this framework, differ in important ways by implicating a very different form of neural suppression. Our subjects were not asked to ignore distracting stimuli or inhibit a prepotent response. Instead, our approach involves a low-level motion discrimination task that likely involves inhibitory center-surround receptive field mechanisms in middle temporal cortical area [22–27]. We also considered the possibility that attentional differences might underlie our results. If high-IQ individuals were somehow less attentive to large moving stimuli, such attentional effects, even if unconscious, would implicate top-down processes. We, however, find that explanation highly unlikely. Our subjects’ only task was to discriminate motion direction of a single stimulus presented in isolation. This absence of competing stimuli along with brief stimulus durations (~100ms) precludes most top-down attentional effects [9]. In study 2, stimulus sizes were randomly interleaved, ruling out differences in sustained attention. Additionally, when stimuli were presented at low contrast, we found a positive trend between IQ and performance with large moving stimuli (Figure 4C)—a finding inconsistent with top-down attentional biases against large stimuli. Finally, as outlined above, the behavioral results reported here are believed to reflect neural center-surround suppression [22, 25, 27]. These suppressive mechanisms are found both in awake [22, 25] and anesthetized animals [23], further ruling out a possible role of attention.

Overall, our results highlight the fundamental importance of suppression in neural processing. Suppressive mechanisms play critical roles in low-level sensory processing, where they enable our perceptual systems to efficiently process an enormous amount of incoming sensory information [8, 10, 11]. Suppression plays an analogous role in intelligent cognition [15–17, 20, 21], contributing to overall neural efficiency [43]. While above we outlined an information-processing framework for the link between perceptual suppression and intelligence, we can only speculate about underlying neural mechanisms. Based on prior work [12–19, 42], we posit that the efficacy of neural suppression could provide a mechanistic explanation of our results. However, neural suppression is not a unitary mechanism but includes a broad range of inhibitory processes. Many such processes are only weakly related with one another, and only some strongly predict IQ scores [44, 45], namely measures of attentional and working-memory control over distracting information [16–18]. To determine whether SI is related to these higher-level suppressive processes, we measured working-memory performance using a three-back task that incorporates highly distracting lure targets (Supplemental Experimental Procedures). Consistent with earlier results [16–18], we found that subjects’ performance on distracting lure trials was correlated with IQ scores (r = 0.55, p = 0.001), while target and nontarget trial performance was not (r < 0.25, p > 0.19). Notably, SI was correlated with lure trial performance (r = 0.43, p = 0.016), but not with performance on other types of trials (r < 0.23, p > 0.22). These results link the efficacy of low-level perceptual suppression with a measure of top-down suppression that has been linked with IQ. Of course, bottom-up visual and top-down working-memory suppression involve very different neural mechanisms. However, we speculate that different biological instantiations of suppression might, at least in part, depend on similar underlying computations. One possible candidate is normalization, a divisive neural computation that may underlie operations in a wide range of brain systems, ranging from perceptual suppression to decision making [8].

In conclusion, we report a strong link between low-level sensory discriminations and intelligence, based on a simple visual task that involves reasonably well-understood neural mechanisms of motion processing, spatial suppression, and evidence accumulation [22, 24, 25, 27, 46]. As such, SI provides a tractable paradigm for investigating sensory correlates of intelligence.

Supplemental Information

Supplemental Information includes Supplemental Experimental Procedures and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2013.04.053.

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