

A Strong Interactive Link between Sensory Discriminations and Intelligence

Michael D. Melnick,¹ Bryan R. Harrison,² Sohee Park,³ Loisa Bennetto,² and Duje Tadin^{1,4,*}

¹Department of Brain and Cognitive Sciences, Center for Visual Science

²Department of Clinical and Social Sciences in Psychology University of Rochester, Rochester, NY 14627, USA

³Department of Psychology, Vanderbilt University, Nashville, TN 37240, USA

⁴Department of Ophthalmology, University of Rochester Medical Center, Rochester, NY 14642, USA

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.

We first tested the hypothesized link between perceptual suppression and IQ in subjects who completed a short-form Wechsler Adult Intelligence Scale III (WAIS-III) [31]. The results (study 1) revealed a significant correlation between IQ and SI (Figure 2A; $r = 0.64$; $p = 0.02$). To test the robustness and replicability of this finding, in study 2 we introduced several methodological and stimulus changes ([Supplemental Experimental Procedures](#)), including the administration of the full-length WAIS-IV [32]. Again, we found that SI strongly correlates with IQ (Figure 2B; $r = 0.71$; $p = 10^{-9}$; 95% confidence interval [CI] = [0.55, 0.82]). The observed relationship between SI and IQ is considerably stronger than those reported for other sensory measures [2–4] and approaches in magnitude correlations between full-scale IQ and WAIS-IV primary indexes (ranging between 0.72 and 0.86) [32].

To test the robustness of the SI-IQ link, we carried out a Monte Carlo simulation using study 2 data. We generated 9,999 data sets, each consisting of 15 subjects randomly sampled without replacement, and computed the SI-IQ correlation for each data set. The resultant correlation distribution (Figure 2C) is positively skewed with median $r = 0.72$ (95% CI = [0.43, 0.89]). Notably, nearly all (93.3%) of the obtained correlations were statistically significant, indicating that a relatively small sample size is sufficient to reveal the SI-IQ link.

The two studies presented here differ in methods and stimulus parameters ([Supplemental Experimental Procedures](#)), yet both reveal strong SI-IQ links. Stimulus size differences (Figure 1C), however, preclude a direct comparison of SI values. To circumvent this problem, we fitted each subject's data with a simple exponential model ($a \times e^{bx}$), where the scale parameter, a , determines the lower asymptote, while the slope, b , is an estimate of suppression strength that is not explicitly linked to specific stimulus sizes (Figure 1C). Importantly, for both data sets, the exponential slope and SI are highly correlated ($r > 0.996$). The combined distribution of slope estimates again reveals that as the stimulus size increases, high IQ is linked with increasing motion perception impairments (Figure 2D; $r = 0.68$; $p = 10^{-10}$; 95% CI = [0.53, 0.80]).

Next, we examined the relationship between SI and WAIS-IV index scores (study 2). Sensory measures tend to be better

*Correspondence: duje@cvs.rochester.edu



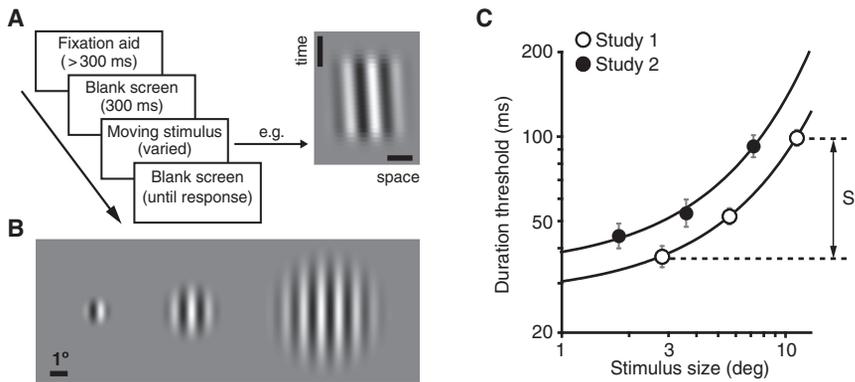


Figure 1. Measurement of Spatial Suppression: Task, Stimuli, and Group-Level Results

(A) The sequence of events constituting a single trial. Subjects' task was to simply identify motion direction of a briefly presented moving stimulus. The space-time plot illustrates a rightward-moving stimulus. The depicted stimulus duration (53 ms) corresponds to the average threshold for the 3.6° stimulus size (see C). Vertical and horizontal scale bars represent 10 ms and 1°, respectively.

(B) Three stimulus sizes used in study 2. Only one stimulus was shown on each trial.

(C) The effect of stimulus size on duration thresholds for discriminating motion direction. Data were fit with an exponential model ($a \times e^{bx}$, $R^2 > 0.993$). Slope, b , is 0.116 and 0.139 for study 1

and study 2, respectively. As detailed in [Supplemental Experimental Procedures](#), raw threshold values cannot be compared across studies. Arrows illustrate the computation of SI, defined as the difference of \log_{10} thresholds for large and small stimuli; $SI = \log_{10}(\text{large-stimulus threshold}) - \log_{10}(\text{small-stimulus threshold})$. Data are represented as mean \pm SEM.

predictors of the performance aspects of IQ, often exhibiting weak or no relationship with verbal intelligence [33]. In contrast, SI is a good predictor of broad intellectual ability: correlations between SI and the Verbal Comprehension, Perceptual Reasoning, Working Memory, and Processing Speed Indices were $r = 0.69, 0.47, 0.49,$ and 0.50 , respectively ($10^{-3} > p > 10^{-8}$). For the purposes of magnitude comparison, we note that these relationships are in the same range as WAIS-IV interindex correlations (ranging between

0.45 and 0.64) [32]. Additionally, SI strongly correlates with the General Ability Index ($r = 0.69$; $p = 10^{-8}$), a WAIS-IV measure 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; $sr = -0.71$, $p = 10^{-9}$) 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 ($R^2 = 0.52$, $F_{2,50} = 26.7$, $p = 10^{-8}$, variance inflation factor < 1.7). High IQ was associated with lower thresholds for small moving stimuli ($\beta = -0.92$, $t_{50} = -7.2$, $p = 10^{-9}$) and higher thresholds for large moving stimuli ($\beta = 0.72$, $t_{50} = 5.6$, $p = 10^{-6}$). We found analogous results for the four WAIS-IV index scores (all $R^2 > 0.23$, $F_{2,50} > 7.55$, $p < 0.001$), where high IQ was predicted by lower small-stimulus thresholds ($-0.89 < \beta < -0.58$; all $p < 0.006$) and higher large-stimulus thresholds ($0.68 > \beta > 0.41$; all $p < 0.011$). In conclusion, rather than being linked with an overall speeding of motion perception, we found that high IQ is associated

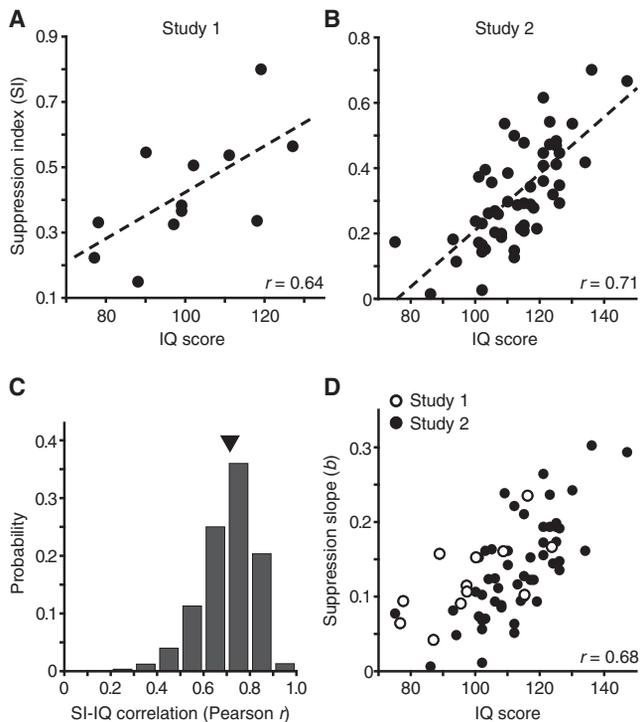


Figure 2. The Relationship between Spatial Suppression and IQ

(A and B) The relationship between SI and IQ in two studies.

(C) Results of a Monte Carlo simulation showing the distribution of SI-IQ correlations for 9,999 random samples (with $n = 15$) from the data shown in (B). The triangle indicates median correlation.

(D) Combined data from two studies with suppression strength estimated from slope, b , derived from exponential fits ($a \times e^{bx}$) to individual subject's data.

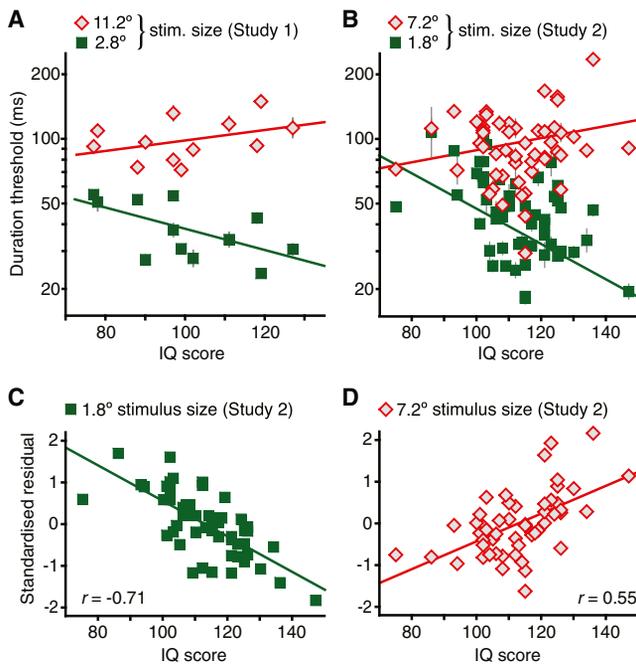


Figure 3. The Relationship between Motion Discrimination Thresholds and IQ
(A and B) The relationship between IQ and duration thresholds for large (\diamond) and small (\blacksquare) moving stimuli. Data are represented as mean \pm SEM.
(C) The relationship between IQ (study 2) and standardized residuals after regressing thresholds for the small stimulus on large-stimulus thresholds.
(D) Same as (C), except that thresholds for the large stimulus were regressed on small-stimulus thresholds.

with increasingly selective low-level sensory processing that favors 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 suppression to spatial summation [22], which is manifested as improved discriminability of low-contrast motions with increasing stimulus size [22, 35, 36]. Thus, by simply reducing stimulus contrast, we can measure perceptual discriminations under a regime largely unaffected by suppressive processes. Such low-contrast stimuli were tested in study 1 (2.8% contrast, other methods unchanged). The results (Figure 4A) showed that as stimulus size increased, thresholds decreased ($F_{2,22} = 20.7$, $p < 10^{-5}$), yielding pronounced spatial summation (i.e., negative SI). Confirming our hypothesis, spatial summation strength did not correlate with IQ (Figure 4B; $r = 0.07$; $p = 0.82$). Instead, for both large and small stimuli, subjects exhibited similar trends toward better performance with increasing IQ (Figure 4C; $r = -0.48$, -0.51 ; $p = 0.10$, 0.09). These results indicate that our main results (Figure 2) are specific to the suppressive effects that occur at suprathreshold contrasts.

Discussion

Our findings endorse Sir Francis Galton and Charles Spearman's original hypotheses [1] and reveal a close

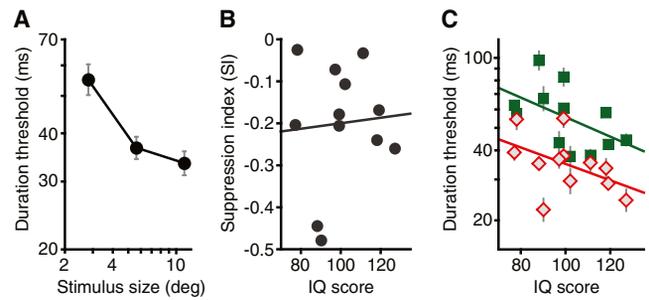


Figure 4. The Relationship between IQ and Motion Discriminations at Low Contrast

(A) The effect of stimulus size on duration thresholds for discriminating motion direction at low contrast. Data are shown as mean \pm SEM.
(B) The relationship between SI and IQ for low-contrast stimuli.
(C) The relationship between IQ and duration thresholds for large (\diamond) and small (\blacksquare) moving stimuli at low contrast. Data are represented as mean \pm SEM.

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 [18] 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 [24, 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>.

Acknowledgments

This work was funded by National Institutes of Health grant EY019295 (to D.T.) and Core grant P30 EY001319. We thank Benjamin Hayden, Andrew Tomarken, Florian Jaeger, Steven Piantadosi, Jessica Cantlon, and Philip Jaekl for comments on the manuscript and Heathman Nichols for assistance. Experimental procedures were approved by institutional review boards at Vanderbilt University and the University of Rochester. All subjects provided written consent.

Received: July 24, 2012
Revised: April 11, 2013
Accepted: April 18, 2013
Published: May 23, 2013

References

1. Evans, R.B., and Deary, I.J. (1994). Sensory discrimination and intelligence: postmortem or resurrection? *Am. J. Psychol.* *107*, 95–115.
2. Jensen, A.R. (2006). *Clocking the Mind: Mental Chronometry and Individual Differences*, First Edition (Amsterdam: Elsevier).
3. Deary, I.J. (2012). Intelligence. *Annu. Rev. Psychol.* *63*, 453–482.
4. Sheppard, L.D., and Vernon, P.A. (2008). Intelligence and speed of information-processing: A review of 50 years of research. *Pers. Individ. Dif.* *44*, 535–551.
5. Deary, I.J., McCrimmon, R.J., and Bradshaw, J. (1997). Visual information processing and intelligence. *Intelligence* *24*, 461–479.
6. Eriksen, B.A., and Eriksen, C.W. (1974). Effects of noise letters upon identification of a target letter in a nonsearch task. *Percept. Psychophys.* *16*, 143–149.
7. Marois, R., and Ivanoff, J. (2005). Capacity limits of information processing in the brain. *Trends Cogn. Sci.* *9*, 296–305.
8. Carandini, M., and Heeger, D.J. (2012). Normalization as a canonical neural computation. *Nat. Rev. Neurosci.* *13*, 51–62.

9. Kastner, S., and Ungerleider, L.G. (2000). Mechanisms of visual attention in the human cortex. *Annu. Rev. Neurosci.* 23, 315–341.
10. Schwartz, O., and Simoncelli, E.P. (2001). Natural signal statistics and sensory gain control. *Nat. Neurosci.* 4, 819–825.
11. Vinje, W.E., and Gallant, J.L. (2000). Sparse coding and decorrelation in primary visual cortex during natural vision. *Science* 287, 1273–1276.
12. Gazzaley, A., Cooney, J.W., Rissman, J., and D'Esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nat. Neurosci.* 8, 1298–1300.
13. Zanto, T.P., and Gazzaley, A. (2009). Neural suppression of irrelevant information underlies optimal working memory performance. *J. Neurosci.* 29, 3059–3066.
14. Kane, M.J., Bleckley, M.K., Conway, A.R., and Engle, R.W. (2001). A controlled-attention view of working-memory capacity. *J. Exp. Psychol. Gen.* 130, 169–183.
15. Conway, A.R.A., Kane, M.J., and Engle, R.W. (2003). Working memory capacity and its relation to general intelligence. *Trends Cogn. Sci.* 7, 547–552.
16. Gray, J.R., Chabris, C.F., and Braver, T.S. (2003). Neural mechanisms of general fluid intelligence. *Nat. Neurosci.* 6, 316–322.
17. Burgess, G.C., Gray, J.R., Conway, A.R., and Braver, T.S. (2011). Neural mechanisms of interference control underlie the relationship between fluid intelligence and working memory span. *J. Exp. Psychol. Gen.* 140, 674–692.
18. Engle, R.W., Tuholski, S.W., Laughlin, J.E., and Conway, A.R.A. (1999). Working memory, short-term memory, and general fluid intelligence: a latent-variable approach. *J. Exp. Psychol. Gen.* 128, 309–331.
19. McNab, F., and Klingberg, T. (2008). Prefrontal cortex and basal ganglia control access to working memory. *Nat. Neurosci.* 11, 103–107.
20. Dempster, F.N. (1991). Inhibitory processes: A neglected dimension of intelligence. *Intelligence* 15, 157–173.
21. Jung, R.E., and Haier, R.J. (2007). The Parieto-Frontal Integration Theory (P-FIT) of intelligence: converging neuroimaging evidence. *Behav. Brain Sci.* 30, 135–154, discussion 154–187.
22. Tadin, D., Lappin, J.S., Gilroy, L.A., and Blake, R. (2003). Perceptual consequences of centre-surround antagonism in visual motion processing. *Nature* 424, 312–315.
23. Born, R.T., and Tootell, R.B.H. (1992). Segregation of global and local motion processing in primate middle temporal visual area. *Nature* 357, 497–499.
24. Born, R.T., Groh, J.M., Zhao, R., and Lukasewycz, S.J. (2000). Segregation of object and background motion in visual area MT: effects of microstimulation on eye movements. *Neuron* 26, 725–734.
25. Churan, J., Khawaja, F.A., Tsui, J.M.G., and Pack, C.C. (2008). Brief motion stimuli preferentially activate surround-suppressed neurons in macaque visual area MT. *Curr. Biol.* 18, R1051–R1052.
26. Tadin, D., and Lappin, J.S. (2005). Linking psychophysics and physiology of center-surround interactions in visual motion processing. In *Seeing Spatial Form*, M.R.M. Jenkin and L.R. Harris, eds. (Oxford: Oxford University Press), pp. 279–314.
27. Tadin, D., Silvano, J., Pascual-Leone, A., and Battelli, L. (2011). Improved motion perception and impaired spatial suppression following disruption of cortical area MT/V5. *J. Neurosci.* 31, 1279–1283.
28. Betts, L.R., Taylor, C.P., Sekuler, A.B., and Bennett, P.J. (2005). Aging reduces center-surround antagonism in visual motion processing. *Neuron* 45, 361–366.
29. Tadin, D., Kim, J., Doop, M.L., Gibson, C., Lappin, J.S., Blake, R., and Park, S. (2006). Weakened center-surround interactions in visual motion processing in schizophrenia. *J. Neurosci.* 26, 11403–11412.
30. Foss-Feig, J.H., Tadin, D., Schauder, K.B., and Cascio, C.J. (2013). A substantial and unexpected enhancement of motion perception in autism. *J. Neurosci.* 33, 8243–8249.
31. Axelrod, B.N. (2002). Validity of the Wechsler abbreviated scale of intelligence and other very short forms of estimating intellectual functioning. *Assessment* 9, 17–23.
32. Psychological Corporation. (2008). *WAIS-IV Technical and Interpretive Manual* (San Antonio: Pearson).
33. Crawford, J.R., Deary, I.J., Allan, K.M., and Gustafsson, J. (1998). Evaluating competing models of the relationship between inspection time and psychometric Intelligence. *Intelligence* 26, 27–42.
34. Duckworth, A.L., Quinn, P.D., Lynam, D.R., Loeber, R., and Stouthamer-Loeber, M. (2011). Role of test motivation in intelligence testing. *Proc. Natl. Acad. Sci. USA* 108, 7716–7720.
35. Watson, A.B., and Turano, K. (1995). The optimal motion stimulus. *Vision Res.* 35, 325–336.
36. Anderson, S.J., and Burr, D.C. (1991). Spatial summation properties of directionally selective mechanisms in human vision. *J. Opt. Soc. Am. A* 8, 1330–1339.
37. Deary, I.J., Bell, P.J., Bell, A.J., Campbell, M.L., and Fazal, N.D. (2004). Sensory discrimination and intelligence: testing Spearman's other hypothesis. *Am. J. Psychol.* 117, 1–18.
38. Meyer, C.S., Hagmann-von Arx, P., Lemola, S., and Grob, A. (2010). Correspondence between the general ability to discriminate sensory stimuli and general intelligence. *J. Individ. Differ.* 31, 46–56.
39. Lindenberger, U., and Baltes, P.B. (1994). Sensory functioning and intelligence in old age: a strong connection. *Psychol. Aging* 9, 339–355.
40. Regan, D. (2000). *Human Perception of Objects* (Sunderland: Sinauer Press).
41. Pack, C.C., Hunter, J.N., and Born, R.T. (2005). Contrast dependence of suppressive influences in cortical area MT of alert macaque. *J. Neurophysiol.* 93, 1809–1815.
42. Ophir, E., Nass, C., and Wagner, A.D. (2009). Cognitive control in media multitaskers. *Proc. Natl. Acad. Sci. USA* 106, 15583–15587.
43. Neubauer, A.C., and Fink, A. (2009). Intelligence and neural efficiency. *Neurosci. Biobehav. Rev.* 33, 1004–1023.
44. Friedman, N.P., and Miyake, A. (2004). The relations among inhibition and interference control functions: a latent-variable analysis. *J. Exp. Psychol. Gen.* 133, 101–135.
45. Friedman, N.P., Miyake, A., Corley, R.P., Young, S.E., Defries, J.C., and Hewitt, J.K. (2006). Not all executive functions are related to intelligence. *Psychol. Sci.* 17, 172–179.
46. Gold, J.I., and Shadlen, M.N. (2007). The neural basis of decision making. *Annu. Rev. Neurosci.* 30, 535–574.

**A Strong Interactive Link between
Sensory Discriminations and Intelligence**

Michael D. Melnick, Bryan R. Harrison, Sohee Park, Loisa Bennetto, and Dujie Tadin

Supplemental Experimental Procedures

Subjects

Sixty-seven subjects (33 females) participated in two studies. Study 1 included typical subjects ($n = 12$) described in [29], who completed four-item short form WAIS-III [31] (mean IQ = 100.4, st. dev. = 15.9, derived from Similarities, Vocabulary, Block design and Matrix reasoning tests). All Study 1 subjects were screened for history of mental illness or neurological disorders. Study 2 subjects ($n = 53$) completed full WAIS-IV [32] (mean IQ = 112.9, st. dev. = 12.8). The average age in the two studies was 36 (st. dev. = 7.2) and 33.1 (st. dev. = 13.4). Partialing out age did not change correlations between SI and IQ (Study 1: $P > 0.98$; Study 2: $P > 0.93$). In Study 1, we also collected education level data, measures of social functioning and schizotypal personality tendencies [29]. Partialing out each of these measures resulted in small, non-significant increases in the SI-IQ correlation ($P > 0.79$). Subjects were recruited from the general population via newspaper and online advertisements (www.craigslist.org). Inclusion criteria were normal or corrected-to-normal visual acuity and absence of visual pathology. For 15 subjects, we made full measurements of near (reading distance) and far (at 20 ft.) visual acuity. As expected from our recruitment criteria, measured acuities clustered tightly around “normal” visual acuity (median near/far acuity in logMAR units = 0/0; 1st quartile = 0/-0.15; 3rd quartile = 0.05/0). This sub-sample exhibited strong correlation between SI and IQ ($r = 0.67$, $P = 0.003$), but no significant links between acuity and either IQ or SI (for both near and far acuity; all $|r| < 0.28$, all $P > 0.31$). Partialing out near acuity increased SI-IQ correlation to 0.79, while partialing out far acuity slightly decreased SI-IQ correlation to 0.65. Note that because our recruiting procedure excluded individuals with vision problems this result does not address links between acuity and intelligence that are found in individuals with moderate and poor acuity [39].

Data Analysis

All correlations (Pearson r) are uncorrected. Parametric analyses were used as all data passed normality tests (as assessed by Chi-square, Lilliefors and Jarque-Bera tests). We also analyzed the relationship between SI and IQ using rank-order correlations and found very similar relationships (Study 1 $r_s = 0.72$; Study 2 $r_s = 0.70$). All tests are two-tailed. Correlation differences were tested using a variant of Fisher’s r-to-z transformation for correlated samples [47]. Standardized weights are reported in the multiple regression analysis.

Two distant outliers (Study 2) were excluded because their data was 3.2 inter-quartile ranges beyond the third quartile (these subjects had trouble performing the motion task and were not included in the mean IQ and sample size reported above).

Stimuli

Stimuli were created in MATLAB and shown on linearized displays. Study 1 used a CRT monitor (800 x 600 resolution, 120Hz, 60.5 cd/m² background). Viewing distance was 83 cm. Study 2 used a custom 360Hz DLP projector [48](1280 x 720 resolution, 113.7 cd/m² background). Viewing distance was 146 cm.

Stimuli were briefly presented sine-wave gratings, moving either leftward or rightward with speed of 4°/s (Figure 1A). Peak stimulus contrast was 42%, which is sufficiently high to guarantee spatial suppression but low enough to avoid ceiling effects [22]. Stimulus spatial frequency was low (1 cycle/°), excluding the possibility that typical acuity variations limited task performance. Stimulus duration was defined as the full-width at half-height of the temporal envelope [27], which was either Gaussian (Study 1) or trapezoidal [27] (Study 2). Note that these envelope differences preclude raw threshold comparison between studies (e.g., because of long Gaussian ‘tails,’ the effective duration of Study 1 stimuli was longer). Importantly, the exact definition of duration affects only the vertical position of the data in Figures 1C and 3A, B, having no effect on scale-free estimates of suppression strength (Figure 2).

Stimulus size was defined by the stationary spatial envelope through which moving gratings were shown. Each study included three different stimulus sizes (Figure 1B), selected on the basis of previous results [22] with an aim to include both small stimuli where performance is high and large stimuli where spatial suppression reduces motion sensitivity. This envelope was either Gaussian (Study 1) or raised cosine (Study 2). In both cases, size was measured as the visible stimulus diameter, with visibility defined as local contrast higher than 1% (choosing other visibility cutoffs (0.1-3%) had negligible effects on the results). Different sizes were run in separate, randomized blocks (Study 1) or were interleaved within each block (Study 2).

Procedure

On each trial, a moving stimulus was presented and a subject simply identified perceived motion direction (leftward vs. rightward). Feedback was provided. Unlike conventional measures of inspection time [2, 4], discriminations of stimulus motion are not confounded by visual persistence, precluding the need for a backward mask. The dependent variable was $\log_{10}(\text{stimulus duration})$ [22, 27-29, 48]. For each condition, eight duration thresholds (82% correct) were estimated by QUEST staircases [49]. The first two were measured on a separate day and used as practice. The highest and lowest results were excluded and the remaining thresholds were averaged. This yielded very high split-half reliabilities. The average (over three sizes) split-half reliability was 0.978 and 0.985 for Study 1 and 2, respectively. The QUEST procedure is designed to ‘work’ in the log space [49], directly estimating $\log_{10}(\text{threshold})$. Thus, data presented here are not log transformed, but rather they were natively estimated in the log space.

Working-Memory Task

Subjects ($n = 30$ from Study 2) performed a 3-back match-to-sample task. Stimulus bank consisted of 100 face images [50] and 100 most frequently used nouns taken from the Academic Word List [51]. Face images were scaled to 3.8° x 5.2°, while words were 3.8° wide. Each

stimulus was presented for 1s. Subjects' task was to respond if the presented stimulus (either a face or a word) matched the stimulus presented 3 trials behind (target trials, occurred on ~25% of total trials). Lure trials were defined as trials associated with either a 2-back, 4-back or 5-back match (~25% of trials). These are high interference trials that require suppression of lures [16]. Trials without a preceding match were non-target trials (~50% of trials). Feedback was provided. Standard deviations of between-subjects results for different trial types were relatively constant, ranging between 11.3% and 15.2%. For this data set, the correlation between SI and IQ scores was 0.65.

Supplemental References

47. Steiger, J.H. (1980). Tests for comparing elements of a correlation matrix. *Psychol. Bull.* 87, 245-251.
48. Glasser, D.M., and Tadin, D. (2011). Increasing stimulus size impairs first-but not second-order motion perception. *J Vision* 11.
49. Watson, A.B., and Pelli, D.G. (1983). QUEST: a Bayesian adaptive psychometric method. *Percept. Psychophys.* 33, 113-120.
50. Thomaz, C.E., and Giraldi, G.A. (2010). A new ranking method for principal components analysis and its application to face image analysis. *Image Vision Comput* 28, 902-913.
51. Coxhead, A. (2000). A new academic word list. *Tesol Quart* 34, 213-238.