
Article:

Castronovo, J and Delvenne, JFCM (2013) Superior numerical abilities following early visual deprivation. Cortex, 49 (5). 1435 - 1440. ISSN 1973-8102

https://doi.org/10.1016/j.cortex.2012.12.018

Superior numerical abilities following early visual deprivation

Julie Castronovo[1] and Jean-François Delvenne[2]

[1] Department of Psychology, University of Hull,
Hull, HU6 7RX, United Kingdom
[2] Institute of Psychological Sciences, University of Leeds,
Leeds, LS2 9JT, United Kingdom

All correspondence and reprint requests should be addressed to:

Julie Castronovo
Department of Psychology
University of Hull
Hull, HU6 7RX
United Kingdom
E-Mail: **J.Castronovo@hull.ac.uk**

ABSTRACT

In numerical cognition vision has been assumed to play a predominant role in the elaboration of the numerical representations and skills. However, this view has been recently challenged by the discovery that people with early visual deprivation not only have a semantic numerical representation that shares the same spatial properties with that in sighted people, but also have better numerical estimation skills. Here, we show that blind people's superior numerical abilities can be found in different numerical contexts, whether they are familiar or more general. In particular, we found that blind participants demonstrated better numerical estimation abilities than sighted participants in both an ecologic footstep and an unfamiliar oral verbal production task. Blind participants also tend to show greater working memory skills compared to sighted participants. These findings support the notion that vision is not necessary in the development of numerical cognition and indicate that early visual deprivation may even lead to a general enhancement in numerical estimation abilities. Moreover, they further suggest that blind people's greater numerical skills might be accounted by enhanced high-level cognitive processes, such as working memory.

Keywords: blindness, numerical estimation.

1. INTRODUCTION

Vision has for a long time been suggested to be central in numerical cognition for several reasons. Firstly, vision constitutes a predominant sensory modality in humans with significant advantages over other sensory modalities, notably in accessing numerical information. Vision allows greater amount of information to be processed, greater precision, easier access to distant objects, and greater attentional modulations (i.e., sharp focus, easy capture) (Thinus-Blanc and Gaunet, 1997). Secondly, vision allows numerical information to be processed simultaneously, while other senses mainly involve sequential processing, which has been found to be more complex than simultaneous numerical processing in children (Mix, 1999), adults (Tokita and Ishiguchi, 2012) and animals (Nieder et al., 2006). Thirdly, vision has predominantly been used in research on numerical cognition, particularly in the study of subitizing (i.e., rapid and accurate process of up to three or four items). For example, in the "object-file model", subitizing corresponds to a visual pre-attentive non-numerical process foundational to the acquisition of numerical cognition, with the later acquisition of numerical skills following the development of visuo-spatial cerebral circuits (Simon, 1997, 1999; Trick and Pylyshyn, 1994). Finally, the number sense, which corresponds to humans' innate approximate intuition about numerosities and largely considered as constituting the foundations of numerical cognition (see Piazza, 2010, for a review), has been labelled as visual (Burr and Ross, 2008; Ross and Burr, 2010; Stoianov and Zorzi, 2012). Following the observation that the perceived numerosity of a set of objects can be modified by adaptation similarly to other primary visual properties (e.g., colour), Burr and Ross (2008) conceptualised "the visual number sense". Their conclusion is that numerosity can be seen as a primary visual attribute and that the primary visual system entails the capacity to approximate numerosities. The idea of a “visual number sense” has been further supported by Stoianov and Zorzi’s (2012) hierarchical generative model, showing that visual numerosities constitute invariants, which can be extracted and coded independently from other visual attributes.

The concept of a “visual number sense” implies a central role of vision in the development of numerical representations and skills. However, recent studies on numerical cognition and blindness have challenged this view. A growing set of data has indicated that early blindness does not preclude the elaboration of a semantic numerical representation (SNR) with similar spatial properties to those postulated in sighted people: a mental continuum oriented from left to right (Dehaene, 1997; Dehaene et al., 1993; Fias et al., 1996; Zorzi et al., 2006). Compared to sighted people, congenitally blind people show similar: distance, size and SNARC effects when submitted to numerical comparison (Castronovo and Seron, 2007a; Szücs and Csépe, 2005) and parity judgement tasks (Castronovo and Seron, 2007a); pseudoneglect (leftward bias) in numerical bisection task (Cattaneo et al., 2011); numerical spatial attentional shift in detection tasks (Salillas et al., 2009) and physical line bisection tasks (Cattaneo et al., 2010). Regarding the third property of SNR, its obedience to Weber’s law (i.e., approximate numerical processing with increasing numerosity), congenitally blind participants’ performances in numerical estimation tasks present as expected the signature to Weber’s law (i.e., constant coefficients of variation across target size) (Castronovo and Seron, 2007b; Ferrand et al., 2010).

Altogether, those data clearly indicate that vision is not essential in the development of SNR with similar properties as in sighted people. More importantly and surprisingly, early blindness might even have a positive impact on numerical abilities. Indeed, congenitally blind participants demonstrate greater estimation skills than sighted participants, especially when submitted to numerical estimation tasks involving touch and proprioception: smaller variability and greater accuracy in their estimates in a small (up to 9) (Ferrand et al., 2010) and large numerical range (up to 64) (Castronovo and Seron, 2007b). These high numerical performances in blind people suggest that early blindness and its consecutive experience in accessing and processing numerical information might lead to greater mapping abilities between symbolic numerical representations (verbal numerals) and their corresponding magnitudes. They could also reflect the use in blind people when performing numerical tasks of enhanced high-level cognitive resources, such as working memory (WM) (Salillas et al., 2009; Szücs and Csépe, 2005), since: 1) WM and numerical skills appear to be linked (De Smedt et al., 2009; Simmons et al., 2012); 2) blind children present greater WM skills than sighted children (Hull and Mason, 1995; Lee Swanson and Luxenberg, 2009); 3) compared to sighted children, blind children seem to rely on WM rather than on finger counting when submitted to counting task (Crollen et al., 2011a) ; 4) neuro-imaging (event-related brain potentials) data suggest that blind people apply high cognitive resources (cognitive P300 component), such as WM, when processing numerical information (Salillas et al., 2009; Szucs and Csepe, 2005).

Here, we extend our previous findings by showing that congenitally blind people's great estimation skills are not tied to a particular modality (i.e., tactile) in which they might have greater acuity (Goldreich and Kanics, 2003), neither to particular numerical contexts close to their daily life experience in using numerical information (i.e., locomotion involving quantitative judgements through proprioception), but can also be extended to more general unfamiliar numerical contexts requiring verbal, non-tactile numerical processing. Moreover, we provide further support to the assumption that blind people's greater numerical skills might also be accounted by enhanced high-level cognitive processes, such as WM.

2. METHODS

2.1.Participants

We tested a group of congenitally blind participants and a group of sighted participants matched in age and sex. All participants gave informed consent.

Blind participants were 11 volunteers (8 men; 9 right-handed), presenting different levels of education (8 high school level, 3 university level) and different histories of visual impairment: prematurity, retinoblastoma, glaucoma, Leber's congenital amaurosis and septo optic hypoplasia. All were proficient Braille readers since childhood, aged between 24 and 65 (mean age = 43, standard deviation = 13).

Sighted participants were 11 volunteers (8 men, 10 right-handed), aged between 25 and 61 (mean age = 43, standard deviation = 12). All sighted participants had university education level. They were blindfolded to perform the different tasks.

2.2. Tasks and procedure

All participants were submitted to two numerical production tasks: a footstep production (FP) task and an oral verbal production (OVP) task. They also undertook three WM tasks: forward-digit, backward-digit and word span tests. The tasks were conducted through two sessions, in which both estimation tasks were undertaken twice. The digit span tests ran in the first session, the word span test in the second session.

In both production tasks, the same target numbers as in Castronovo and Seron (2007b) ranging from 5 to 64 were used. Each target number was presented 16 times across 8 blocks in each production task (2 presentations/block, 4 blocks/session) according to a fixed pseudo-random order (no consecutive repetition of the same target number). The two tasks were inter-mixed within each session, with half of the participants in each group starting with the FP task, while the other half started with the OVP task. Each task had 8 practice trials.

In the FP task, participants were instructed to produce footsteps, while holding on to a bar fixed on the wall, until they have approximately reached the numerosity corresponding to the target number heard. To avoid the use of a counting strategy, participants had to continuously repeat “da” while producing their footsteps, inducing articulatory suppression. Performance was video-recorded.

In the OVP task, participants had to repeatedly produce the non-word “bam” until they have approximately reached the numerosity of the target number. To avoid the use of a counting strategy, participants had to produce their responses under speed pressure. Responses were audio-recorded. In both tasks, participants had to report their completion by saying “stop”.

The digit span word span tests were adapted from the Automated Working Memory Assessment (Alloway, 2007) (see Appendix). Both digit span tests started with a two-trial block of 2 numbers. The forwards digit span test ended with a two-trial block of 9 numbers; the backwards digit span test with a two-trial block of 8 numbers. Two practice trials of 2 and 3 numbers were introduced. A trial was successful (scored 1) when the sequence of numbers was recalled in the correct order. A trial was unsuccessful (scored 0) when the sequence of numbers was not recalled in the correct order or when it comprised a number not presented in the original sequence. In the word span test, participants had to recall increasing sequences of words in the correct order. The test went from a three-trial block of 2 words to a three-trial block of 7 words. Two practice trials of 2 and 3 words were initially undertaken. A trial was recorded as successful when participants recalled a word sequence in the right order. It was recorded as unsuccessful, when participants recalled a word not presented in the original sequence or when recalling the sequence of words in the incorrect order. A total score was computed in each test. A test was put to an end after 2 consecutive unsuccessful trials within a block in the digit span tests and 3 consecutive trials within a block in the word span test.

3. RESULTS

Similar analyses were conducted in both estimation tasks on target numbers ranging from 14 to 64. Target numbers [5-11] were excluded from the analyses as participants' self reports and preliminary analyses suggested that the use of a counting strategy was difficult to avoid within this range. Coefficients of variation (CV = standard deviation/mean) per target numerosity and for each participant were computed. Signature of Weber's law is found when CVs are constant across target size, as the mean responses and their standard deviation linearly increase in direct proportion with target magnitude (Whalen et al., 1999). Analyses of variance were carried out to investigate whether participants' performances obeyed Weber's law and whether there were any group differences in participants' response variability. Absolute accuracy scores were then computed (|AS| = |response – target number|) and analyses of variance were conducted to look for group differences. Greenhouse-Geisser correction was applied when the assumption of sphericity was violated. Participants WM skills were analysed using one-way ANOVAs. Finally, correlational analyses were carried out to compare participants' performances across the different tasks.

3.1. Footstep Production Task Results

Constant CVs across target size were found in both groups, as a repeated measures Target Number (11) x Group (2) ANOVA indicated the absence of a significant target number effect on CVs, $p > .2$, and the absence of a significant Target Number x Group interaction, $p > .4$. However, sighted participants presented greater variability in their estimations, as the group effect was significant, $F(1, 20) = 15.48$, $p = .001$ (Mean CV = .17, SD = .05 in the sighted group; Mean CV = .10, SD = .05 in the blind group).

Target number had a significant effect on |AS|, $F(1.43, 28.59) = 12.96$, $p < .001$: the larger the target number, the more approximate participants' estimations. Separate ANOVAs indicated that this effect was more pronounced in the sighted group ($F(x, x) = x$; $p < .001$) than in the blind group ($F(x, x) = x$; $p < .01$), as reflected by the significant Target Number x Group interaction, $F(1.43, 28.59) = 4.07$, $p < .05$. Blind participants demonstrated significantly greater estimation skills compared to sighted participants, as the group effect was also significant, $F(1, 20) = 6.36$, $p < .05$ (Mean |AS| = 1.73, SD = 1.81 in the blind group; Mean |AS| = 7.73, SD = 9.4 in the sighted group) (see Figure 1).

Figure 1 about here

3.2. Oral Verbal Production Task Results

In the OVP task, CVs were constant in both groups: non-significant target number effect, $p > .4$, and non-significant interaction between target number and group, $p > .3$. However, similarly as in the FP task, blind participants (Mean CV = .11, SD = .09) presented significantly smaller variability in their estimations than sighted participants (Mean CV = .17, SD = .06), $F(1, 20) = 5.91$, $p < .05$.

On |AS|, there was a significant target number effect, $F(1.25, 24.96) = 8.64$, $p < .005$: the larger the target number, the greater the misestimation. The target number x group interaction did not reach significance, $p > .2$. Importantly, blind participants greater estimation skills were further confirmed, as they significantly showed greater accuracy scores compared to sighted participants, $F(1, 20) = 4.27$, $p < .05$ (Mean |AS| = 2.42, SD = 4.43 in the blind group; Mean |AS| = 9.09, SD = 11.77 in the sighted group) (see Figure 2).

Figure 2 about here

3.3. Working Memory Tasks results

Although, blind participants tend to show greater WM performances compared to sighted participants, in line with previous results on blind children (Lee Swanson and Luxenberg, 2009; Hull and Mason, 1995), there was no significant group effect in the forward-digit span test (Mean = 13.18, SD = 1.99 in the blind group; Mean = 12.00, SD = 2.28 in the sighted group) and the backward-digit span test (Mean = 9.64, SD = 3.41 in the blind group; Mean = 8.82, SD = 3.06 in the sighted group), $p > .2$ and $p > .5$

respectively. In the word span test, blind participants showed a slight, but not significant advantage over sighted participants, F(1, 19) = 3.72, p = .07 (Mean = 11.50, SD = 1.27; Mean = 10.10, SD = 1.91 respectively).

Finally, since WM has been found to predict numerical skills (De Smedt et al., 2009; Simmons et al., 2012), one-tailed correlation analyses across groups were conducted between the different tasks. All WM tests were significantly positively correlated ($p_s < .05$). The CV and |AS| in the FP task significantly negatively correlated with the WM performances in the word span test ($p_s < .05$): the smaller the variability and the misestimation in the FP task, the greater the word span test scores. When controlling for group differences, partial correlations between the word span scores and the FP performances were then non-significant (p > .2 for CV and p > .4 for |AS|). Negative correlation between the |AS| in the FP task and the WM scores in the backward-digit span reached marginal significance: the greater the backward-digit span, the smaller the misestimation in the FP task. Again, when controlling for group differences, partial correlation analysis showed non-significant correlation between the backward-digit span scores and the FP task |AS| (p > .2). No correlations between WM scores and the OVP performances reached significance. Performances (CV and |AS|) within and between the two estimation tasks were significantly correlated (see Table 1).

Table 1 about here

----

4. DISCUSSION

Until recently, vision has been suggested to play a critical role in numerical cognition (Burr and Ross, 2008; Ross and Burr, 2010; Simon, 1997, 1999; Stoianov and Zorzi, 2012; Trick and Pylyshyn, 1994), suggesting that vision is essential in the development of numerical skills. However, new data in blind people suggest that this might not be the case (Castronovo and Seron, 2007a; Cattaneo et al., 2011; Salillas et al., 2009; Szücs and Csépe, 2005). More importantly, early visual deprivation seems to have a positive impact on numerical skills (Castronovo and Seron, 2007b; Ferrand et al., 2010). Here, we provide further evidence for greater numerical skills in blind people compared to sighted people (i.e., less variability, greater accuracy in responses) in numerical contexts, involving different sensory modalities, close to their daily life experience (i.e., in a FP task), as well as in an unfamiliar context (i.e., in a OVP task).

Blind participants' better estimation skills reflect enhanced mapping abilities between symbolic (verbal numerals) and non-symbolic (magnitude) numerical representations. These might be accounted by greater, more efficient experience in accessing and processing numerical information (Castronovo and Göbel, 2012; De Smedt et al., 2009; Mundy and Gilmore, 2009), notably in the sequential mode since touch and audition mainly involve sequential processing of information and the simultaneous vs. sequential nature of the dominant perceptual experience has been found to play a critical role in modelling cognitive functions (Cattaneo et al., 2008). Blind participants' greater mapping skills cannot be accounted by greater level of education (Castronovo and Göbel, 2012), as in average they presented a lower level of education than sighted participants. It can neither be assumed that sighted participants would perform similarly to blind participants in their predominant visual modality. Indeed, whatever the task modality, sighted people demonstrate similar highly approximate numerical estimations (Crollen et al., 2011a; Piazza et al., 2006; Whalen et al., 1999).

Blindness is well-known to lead to the development of compensatory strategies involving high-level cognitive processes, such as attention, to make up for the lack of vision (Collignon et al., 2006; Collignon et al., 2009). Numerical processing might constitute one of the compensatory strategies acquired in the absence of vision to deal with the environment (e.g., use of quantitative judgements in locomotion). Moreover, early visual deprivation might be more likely to entail multisensory (tactile, proprioceptive, auditive) experience with numerical information, rather than being focused on a main sensory modality as in sighted people. The recent findings that multisensory processing of numerical information boosts numerical skills (Jordan and Baker, 2011; Ramani and Siegler, 2008; Siegler and Mu, 2008) appear to support this assumption. Blind people's greater numerical skills might also reflect more controlled numerical process, due to the allocation of enhanced high-cognitive resources, such as WM (Crollen et. al., 2011b; Salillas et al., 2009). Blind participants' tendency to show greater WM spans, as well as the significant correlation between FP performances and WM scores when group differences were not taken into account, are in favour of this hypothesis. Future research would be needed to further investigate these hypotheses, notably with the use of more discriminative WM tasks.

Thie present study opens a new perspective in the study and theorisation of numerical cognition, which would benefit from a multisensory approach. Similarly further research into multisensory and multimodal access to numerical information and its impact on numerical skills could lead to educational benefits in teaching mathematics in young children.

REFERENCES

Alloway TP. The Automated Working Memory Assessment. London: The Psychological Corporation, 2007.

Burr DC and Ross J. A visual sense of number. Current Biology, 18, 425-428, 2008.

Castronovo J and Göbel SM. Impact of high mathematics education on the number sense. PLoS ONE, 7 (4), e33832, 2012.

Castronovo J and Seron X. Numerical estimation in blind subjects: evidence of the impact of blindness and its following experience. Journal of Experimental Psychology: Human, Perception and Performance, 33 (5), 1089-1106, 2007b.

Castronovo J and Seron X. Semantic numerical representation in blind subjects: the role of vision in the spatial format of the mental number line. The Quarterly Journal of Experimental Psychology, 60 (1), 101-119, 2007a.

Cattaneo Z, Fantino M, Silvanto CT, and Vecchi T. Blind individuals show pseudoneglect in bisecting numerical intervals. Attention, Perception and Psychophysics, 73, 1021-1028, 2011.

Cattaneo Z, Fantino M, Tinti C, Silvanto J, and Vecchi T. Crossmodal interaction between the mental number line and peripersonal haptic space representation in sighted and blind individuals. Attention, Perception and Psychophysics, 72 (4), 885-890, 2010.

Cattaneo Z, Vecchi T, Cornoldi C, Mammarella I, Bonino D, Ricciardi E, and Pietrini P. Imagery and spatial processes in blindness and visual impairment. Neuroscience and Biobehavioral Reviews, 32, 1346-1360, 2008.

Collignon O, Renier L, Bruyer R., Tranduy D, and Veraart C. Improved selective and divided spatial attention in early blind subjects. Brain Research, 1075 (1), 175-182, 2006.

Collignon O, Voss P, Lassonde M, and Lepore F. Cross-modal plasticity for the spatial processing of sounds in visually deprived subjects. Experimental Brain Research, 192, 343-358, 2009.

Crollen V, Mahe R, Collignon O, and Seron X. The role of vision in the development of finger-number interactions: finger-counting and finger-montring in blind children. Journal of Experimental Child Psychology, 109, 525-539, 2011a.

Crollen V, Castronovo J, and Seron X. Under- and over-estimation: A bidirectional mapping process between symbolic and non-symbolic representations of number? Experimental Psychology, 58 (1), 39-49, 2011b.

De Smedt B, Janssen R, Bouwens K, Verschaffel L, Boets B, and Ghesquiere P. Working memory and individual differences in mathematics achievement: A longitudinal study from first grade to second grade. Journal of Experimental Child Psychology, 103, 186-201, 2009.

De Smedt B, Verschaffel L, and Ghesquière P. The predictive value of numerical magnitude comparison for individual differences in mathematics achievement. Journal of Experimental Child Psychology, 103, 469-479, 2009.

Dehaene S, Bossini S, and Giraux P. The mental representation of parity and number magnitude. Journal of Experimental Psychology: General, 122, 371–396, 1993.

Dehaene S. The Number Sense. New York: Oxford University Press, 1997.

Ferrand L, Riggs K, and Castronovo J. Subitizing in congenitally blind adults. Psychonomic Bulletin and Review, 17 (6), 840-845, 2010.

Fias W, Brysbaert M, Geypens F, and d’Ydewalle G. The importance of magnitude information in numerical processing: evidence from the SNARC effect. Mathematical Cognition, 2 (1), 95-110. 1996.

Goldreich D and Kanics IM. Tactile acuity is enhanced in blindness. The Journal of Neuroscience, 23 (8), 3439-3445, 2003.

Hull T and Mason H. Performance of blind children on digit-span tests. Journal of Visual Impairment, 89, 166-169, 1995.

Jordan KE and Baker J. Multisensory information boosts numerical matching abilities in young children. Developmental Science, 14 (2), 205-213, 2011.

Lee Swanson H and Luxenberg D (2009). Short-term memory and working memory in children with blindness: support for a domain general or domain specific system? Child Neuropsychology, 15, 280-294, 2009.

Mix KS. Preschoolers’ recognition of numerical equivalence: Sequential sets. Journal of Experimental Child Psychology, 74, 309-332, 1999.

Mundy E and Gilmore CK. Children’s mapping between symbolic and nonsymbolic representations of number. Journal of Experimental Child Psychology, 103, 490-502, 2009.

Nieder A, Diester I, and Tudusciuc O. Temporal and spatial enumeration processes in the primate parietal cortex. Science, 313, 1431-1435, 2006.

Piazza M. Neurocognitive start-up tools for symbolic number representations. Trends in Cognitive Sciences, 14 (12), 542-551, 2010.

Piazza M, Mechelli A, Price CJ, and Butterworth B. Exact and approximate judgements of visual and auditory numerosity: An fMRI study. Brain Research, 1106, 177-188, 2006.

Platt JR and Johnson DM. Localization of position within a homogeneous behaviour chain: Effects of error contingencies. Learning and Motivation, 2, 386-414, 1971.

Ramani GB and Siegler RS. Promoting broad and stable improvement in low-income children’s numerical knowledge through playing number board games. Child Development, 79, 375-394, 2008.

Ross J and Burr DC. Vision senses number directly. Journal of Vision, 10 (2):10, 1-8, 2010.

Salillas E, Grana A, El-Yagoudi R, and Semenza C. Numbers in the Blind’s “Eye”. PLoS ONE, 4 (7), e6357, 2009.

Siegler RS and Mu Y. Chinese children excel on novel mathematics problems even before elementary school. Psychological Science, 18, 759-763, 2008.

Simmons FR, Willis C, and Adams AM. Different components of working memory have different relationships with different mathematical skills. Journal of Experimental Child Psychology, 111, 139-155, 2012.

Simon TJ. Re-conceptualizing the origins of number knowledge: A “non-numerical” account. Cognitive Development, 12, 349-372, 1997.

Simon TJ. The foundations of numerical thinking in a brain without numbers. Trends in Cognitive Sciences, 3, 363-366, 1999.

Stoianov I and Zorzi M. Emergence of a “visual number sense” in hierarchical generative models. Nature Neuroscience, 15 (2), 194-196, 2012.

Szücs D and Csépe V. The parietal distance effect appears in both the congenitally blind and matched sighted controls in an acoustic number comparison task. Neurosciences Letters, 384, 11-16, 2005.

Thinus-Blanc C and Gaunet F. Representation of space in blind persons: vision as a spatial sense? Psychological Bulletin, 121, 20-42, 1997.

Tokita M and Ishiguchi A. Behavioral evidence for format-dependent processes in approximate numerosity representation. Psychonomic Bulletin and Review, 19, 285-293, 2012.

Trick LM and Pylyshynm ZW. Why are small and large numbers enumerated differently? A limited-capacity pre-attentive stage in vision. Psychological Sciences, 3, 363-366, 1994.

Whalen J, Gallistel CR, and Gelman R. Nonverbal counting in humans: The psychophysics of number representation. Psychological Science, 10(2): 130-137, 1999.

Zorzi M, Priftis K, Meneghello F, Marenzi R, and Umilta C. The spatial representation of numerical and non-numerical sequences: Evidence from neglect. Neuropsychologia, 44(7):1061-1067, 2006.

FIGURE CAPTIONS

Figure 1.

Footstep Production Task’s CV (a) and |AS| (b) across target size in the blind and sighted group.

Figure 2.

Oral Verbal Production Task’s CV (a) and |AS| (b) across target size in the blind and sighted group.

Table 1- Correlations between the different tasks and their scores

	Backwards Digit Span	**Word Span**	**Footstep CV**	**Footstep |AS|**	**Oral Verbal CV**	**Oral Verbal |AS|**
Forwards Digit Span	$r = .72^{***}$	$r = .49^{*}$	$r = .04$	$r_s = -.13$	$r = .02$	$r_s = .13$
Backwards Digit Span	-	$r = .38^{*}$	$r = -.18$	$r_s = -.33^{\#}$	$r = .03$	$r_s = -.08$
Word Span		-	$r = -.38^{*}$	$r_s = -.49^{**}$	$r = -.16$	$r_s = -.20$
Footstep CV			-	$r_s = .80^{***}$	$r = .64^{***}$	$r_s = .84^{***}$
Footstep |AS|				-	$r = .62^{***}$	$r_s = .81^{***}$
Oral Verbal CV					-	$r_s = .78^{***}$

* $p < .05$
** $p < .01$
*** $p < .001$
$^{\#}$ Marginally significant ($p = .07$)

APPENDIX

Forwards Digit Span Test

Item	Trial	Response	Score 0/1
1.	Trial 1	1 – 7	
	Trial 2	6 – 3	
2.	Trial 1	5 – 8 – 2	
	Trial 2	6 – 9 – 4	
3.	Trial 1	6 – 4 – 3 – 9	
	Trial 2	7 – 2 – 8 – 6	
4.	Trial 1	4 – 2 – 7 – 3 – 1	
	Trial 2	7 – 5 – 8 – 3 – 6	
5.	Trial 1	6 – 1 – 9 – 4 – 7 – 3	
	Trial 2	3 – 9 – 2 – 4 – 8 – 7	
6.	Trial 1	5 – 9 – 1 – 7 – 4 – 2 – 8	
	Trial 2	4 – 1 – 7 – 9 – 3 – 8 – 6	
7.	Trial 1	5 – 8 – 1 – 9 – 2 – 6 – 4 – 7	
	Trial 2	3 – 8 – 2 – 9 – 5 – 1 – 7 – 4	
8.	Trial 1	2 – 7 – 5 – 8 – 6 – 2 – 5 – 8 – 4	
	Trial 2	7 – 1 – 3 – 9 – 4 – 2 – 5 – 6 – 8	
			Total Score:

Backwards Digit Span Test

Item	Trial	Response	Score 0/1
1.	Trial 1	2 – 4 (4 – 2)	
	Trial 2	5 – 7 (7 – 5)	
2.	Trial 1	6 – 2 – 9 (9 – 2 – 6)	
	Trial 2	4 – 1 – 5 (5 – 1 – 4)	
3.	Trial 1	3 – 2 – 7 – 9 (9 – 7 – 2 – 3)	
	Trial 2	4 – 9 – 6 – 8 (8 – 6 – 9 – 4)	
4.	Trial 1	1 – 5 – 2 – 8 – 6 (6 – 8 – 2 – 5 – 1)	
	Trial 2	6 – 1 – 8 – 4 – 3 (3 – 4 – 8 – 1 – 6)	
5.	Trial 1	5 – 3 – 9 – 4 – 1 – 8 (8 – 1 – 4 – 9 – 3 – 5)	
	Trial 2	7 – 2 – 4 – 8 – 5 – 6 (6 – 5 – 8 – 4 – 2 – 7)	
6.	Trial 1	8 – 1 – 2 – 9 – 3 – 6 – 5 (5 – 6 – 3 – 9 – 2 – 1 – 8)	
	Trial 2	4 – 7 – 3 – 9 – 1 – 2 – 8 (8 – 2 – 1 – 9 – 3 – 7 – 4)	
7.	Trial 1	9 – 4 – 3 – 7 – 6 – 2 – 5 – 8 (8 – 5 – 2 – 6 – 7 – 3 – 4 – 9)	
	Trial 2	7 – 2 – 8 – 1 – 9 – 6 – 5 – 3 (3 – 5 – 6 – 9 – 1 – 8 – 2 – 7)	
			Total Score:

Word Span Test

Item	Trial	Response	Score 0/1
1.	Trial 1	lip bag	
	Trial 2	moon pad	
	Trial 3	come mud	
2.	Trial 1	neck nut pool	
	Trial 2	park cod dip	
	Trial 3	chill dad bean	
3.	Trial 1	mood lunch chart bed	
	Trial 2	lid teach duck barn	
	Trial 3	pet noon mop chick	
4.	Trial 1	lock tip let pack bird	
	Trial 2	cheek dig turn card boot	
	Trial 3	neat men tap cook mark	
5.	Trial 1	pop charm net burn deck jot	
	Trial 2	mill but pin talk peck lead	
	Trial 3	job gum cork learn bud bin	
6.	Trial 1	ditch pot lawn cat book kerb jet	
	Trial 2	got look beach dull gap league	
	Trial 3	map peak nod team bat chin log	
			Total Score:

Figure 1

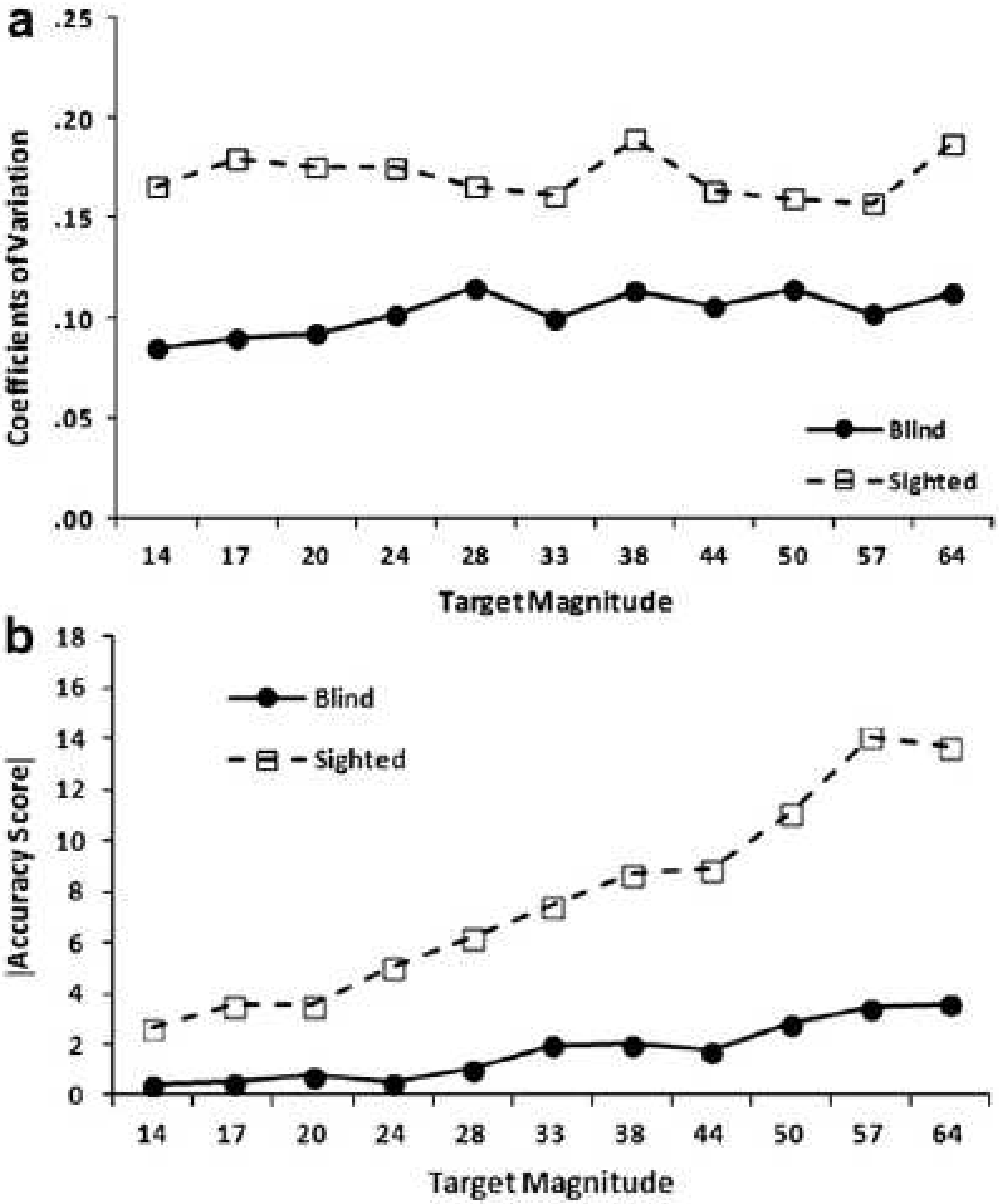
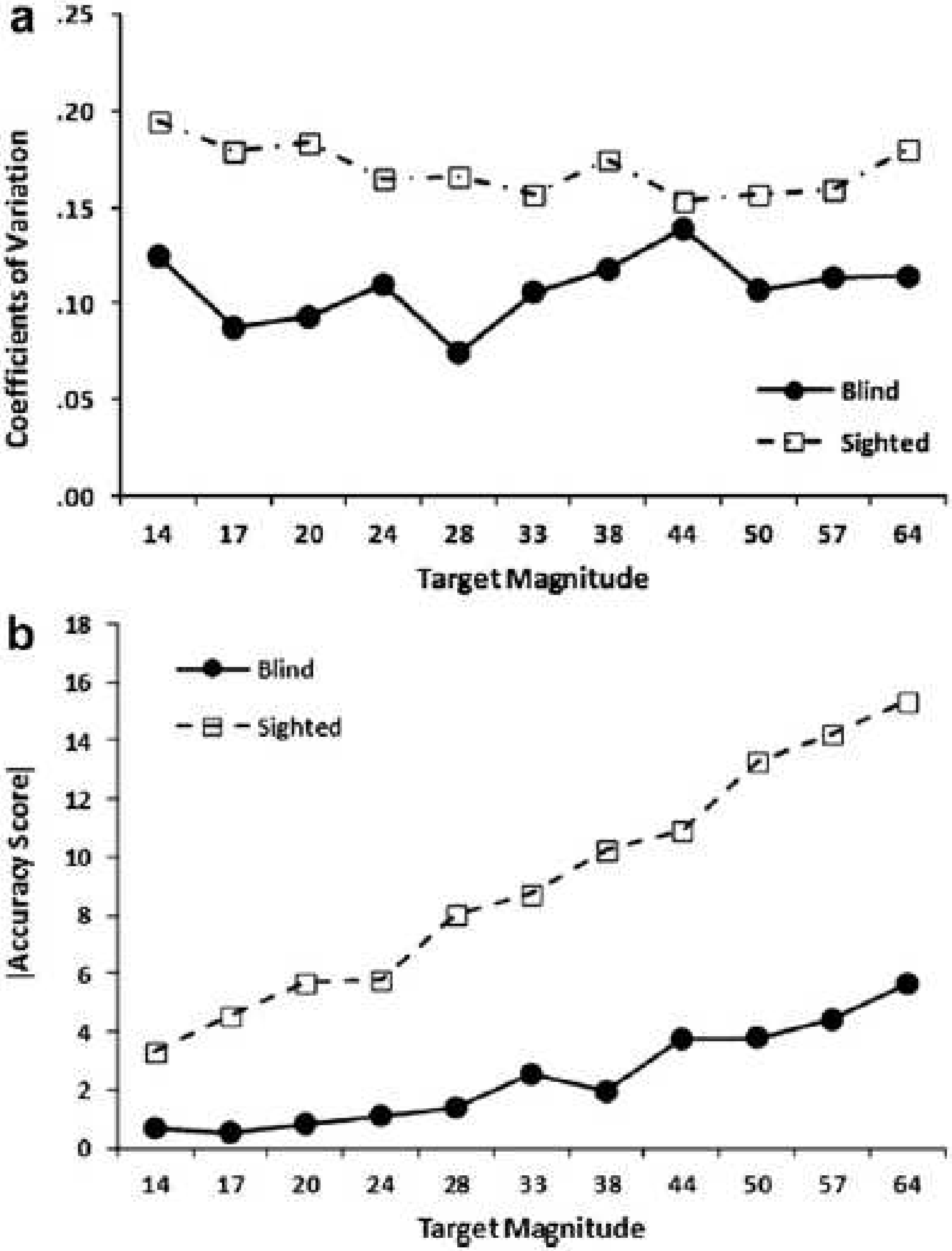

a
.25
.20
.15
.10
.05
.00
Coefficients of Variation
Blind
Sighted
14
17
20
24
28
33
38
44
50
57
64
Target Magnitude
b
18
16
14
12
10
8
6
4
2
0
|Accuracy Score|
Blind
Sighted
14
17
20
24
28
33
38
44
50
57
64
Target Magnitude

Figure 2


a
Coefficients of Variation
.25
.20
.15
.10
.05
.00
14
17
20
24
28
33
38
44
50
57
64
Target Magnitude
Blind
Sighted
b
|Accuracy Score|
18
16
14
12
10
8
6
4
2
0
14
17
20
24
28
33
38
44
50
57
64
Target Magnitude
Blind
Sighted