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Video-game play and non-symbolic numerical comparison

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Abstract
Despite the high prevalence of various genres of video games as a form of leisure, the possible long-term effects of video games on cognitive function remain unclear. In this study, we addressed the possible correlation between playing video games and numerical cognition. Using a cross-sectional design, we compared psychophysical parameters of video-game players (VGP) and non-players (NVGP) as they estimated the number of briefly displayed items in a two-alternative forced choice paradigm. We used linear regression models to analyse the psychophysical data obtained from 32 VGPs and 34 NVGPs. We did not find differences in the accuracy of numerosities estimation between VGPs and NVGPs. However, sensory precision expressed as the just-noticeable difference (JND) was better in VGPs as compared to NVGPs and was positively correlated with time spent gaming each week. We argue that the superiority of VGPs in number processing is most likely not due to specific differences in the neuronal processing within distinct areas underlying numerical cognition but rather related to more general differences in the attentional system, most likely the top–down attentional processes implemented in the dorsal attention network.

KEYWORDS
attentional mechanisms, cross-section study, linear regression models, psychophysics, two-alternative forced choice task, visual number sense

1 | INTRODUCTION

Playing video games is a widespread form leisure activity, especially for young people. More than simply a way to pass time, prior studies suggest that video games may positively influence cognitive functions, among others facilitating a processes called learning to learn. Positive effects on task-switching, top–down attentional control, processing speed, and time perception may be related to playing video games. Particularly, prior studies indicate that video-game players (VGPs) have better top–down control of the negative effects of bottom–up attentional capture, although VGPs do not seem able to shift their spotlight of their attention faster than non-VGPs. Other studies suggest that playing video games may improve working memory and visual short-term memory. Even very early functions in the visual system are affected by video-game play: VGPs have superior contrast sensitivity and show better signal detection, especially if the tasks depend on the dorsal system and peripheral vision. VGPs are more precise with respect of multisensory temporal processing and show an enhanced ability for change detection. Surgeons who play video games have better laparoscopic surgical skills compared to colleagues who do not play. And for older subjects, playing a driving game called neuroracer may be a possibility to counteract the effect of senescence. An increase of grey brain matter of participants aged on

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average 24 years was reported after 2 months of playing Super Mario.23

However, every coin has two sides, spending too much time playing video games has detrimental effects. Some negative consequences of video-game play have been reported: a decreased pro-social and an increased aggressive behaviour of VGPs have been described.24 Exaggerated duration of video gaming may result in addiction.25 As a consequence, the ICD-11 of the World Health Organization includes video-game addiction (6C51 Disorder due to addictive behaviours”.

Another cognitive function is our ability to estimate numerosities appropriately. When we need to estimate the number of items, we do not have to count every single item separately; our number sense enables us to estimate the number without explicit counting. As early as in 1871, it was shown, that the ability to judge the actual number of beans drops from 3 to 15.26 Small numbers (up to 4) are much easier to estimate correctly compared to large numbers. The ability to judge small numbers correctly was introduced as subitizing.27 However, recent investigations prepared the ground for the assumption that the number sense should be viewed as a continuous visual sense, named approximate number system (ANS).28,29 However, there is evidence that the acuity of the ANS does not correlate with arithmetic competence.30 The number sense follows very similar regularities as the perception of other modalities such as brightness, loudness, pressure or weight. The threshold to detect the difference between two stimuli increases with the intensity of the stimulus (Weber’s law). This law explains why it is easier to discriminate distant numbers as closed numbers ‘numerical size effect’28. If the difference between two numbers is constant, it is easier to judge small values than high values ‘numerical distance effect’.28 Another argument for the idea that the number sense follows classical psychophysical properties is the observation, that the numerosities estimation can be adapted: if a subject is exposed to a high numerosities, the subsequently presented numerosities will be massively underestimated.31 The ability to adapt the number sense extends over space, time and sensory modality32 and is remarkably similar in dyscalculic and normal young subjects.33

The sensory nature of the number sense was the origin of our study to address the number sense properties in VGPs compared to non-players (NVGPs). It was earlier shown that action VGPs outperform NVGPs in enumeration tasks and a multiple object tracking task.1,15,34 The error rates of VGPs were smaller compared to NVGPs when subjects had to detect the number of items. However, in this enumeration task, the subjects had to transform the perceived visual stimulus into an abstract representation of number. So it might be possible that these differences between VGPs and NVGPs are related to the later step in processing, that is, to the transformation of the visual information into an abstract representation. Therefore, we decided to use a classical psychophysical approach to compare the core abilities of N/ VGPs to estimate numerosities. We hypothesise that VGP show better resolution in number processing compared to NVGPs.

2 | MATERIALS AND METHODS

We applied classical psychophysical methods to examine the ability of our subjects to estimate the number of items in a visual display.

2.1 | Participants

The 66 participants of our study were either high-school students from local high schools or students of the University of Tuebingen. To avoid different motivation of the experimental groups, the aim of the study was not disclosed during the recruitment of participants as well as during execution of the experiments. We performed psychophysical experiments in accordance with the Declaration of Helsinki and approved by the Ethic Commission of the Medical Faculty of the University of Tuebingen, all participants gave informed consent. Participants were informed that they can terminate the study at any moment without prejudice, penalty, or discomfort.

Only after the experiments, the questionnaire was given to the participants (see Supporting Information, similar to Green and Bavelier1). Among others, the participants identified their weekly video gaming time, their preferred video game as well as the weekly sport time. We assessed the weekly sport time to test the hypothesis that VGPs are in general more active compared to NVGPs.

Table 1 informs about the preferred video games and the weekly gaming times of the VGP cohort. Note that the participants were allowed to indicate multiple games.

Based on our earlier studies,12,20 we used a threshold of 4 h videogame time per week in the self-reports for the group of VGPs resulting in 34 (17 female) NVGPs and 32 (16 female) VGPs. The age distribution of each group is shown in Figure 1A (VGP: M = 19.3, SD = 3.96 years, NVGP: M = 19.2, SD = 3.53 years). There was no significant difference in age (t-test, t(64) = 0.0159, p = 0.9873). In addition, there was no significant difference in age for female and male participants for VGPs and NVGPs (VGP: test, t(30) = 0.7086, p = 0.4841; NVGP: t-test, t(32) = -0.6738, p = 0.5053). The weekly video-game durations are shown in Figure 1B, the NVGPs played on average M = 0.7, SD = 0.97 h whereas the VGPs spend M = 12.8, SD = 10.54 h playing video games per week. The difference in weekly video gaming time is significant (t-test, t(64) = 6.6445, p < 0.0001), there were no significant gender differences (VGP: t-test, t(30) = -0.4969, p = 0.6229). We also asked the amount of weekly sport in our questionnaire shown in Figure 1C. There was no significant difference in the weekly sport time between NVGP (M = 6.5, SD = 3.47 h) and VGP (M = 7.1, SD = 3.47 h) (t-test, t(64) = 0.6089, p = 0.5448). Finally, there was no significant correlation between weekly video gaming time and weekly sport (linear regression, R² = 0.0001, F = 0.0075, p = 0.931).

2.2 | Experimental set-up

Participants were seated 57 cm in front of a monitor (HP1950, 1280 × 1024 pixel extending 37.8 × 30.2°, 60 Hz) by means of a
A computer keyboard was used to record the participants’ responses. Participants could not see the experimenter’s monitor (another HP1950) because their field of vision was restricted by a privacy screen between the two monitors. We used a Fujitsu Esprimo PC (i5-6500 PCU @ 3.20 GHz) running under Windows 10 to perform our study. The stimuli were generated by custom scripts written in MATLAB (The Mathworks, Natick, MA).

### 2.3 Experimental paradigm

We asked our participants to indicate the larger number of black dots within two simultaneously displayed white circles (see Figure 2A) by pressing the left or right arrow key of the keyboard. To make it impossible for the participants to count the number of dots as well as to avoid eye movements, the stimulus was only shown for 200 ms. The fixation cross was continuously presented during the entire trial until the response was given. We did not temporally restrict the response times of the participants; they could respond when wished. The key press in a given trial triggered the onset of the consecutive trial without any additional inter-trial interval.

Each black dot had a diameter of 1.4", the white circle (110 cd/m²) had a diameter of 15.5" centred at 11.3" left and right of the red fixation cross placed at the centre of the screen. The luminance of the grey background was 34 cd/m². The position of each black dot within the white circle was randomly selected in each trial. We did not compensate for overall luminance, cue density, or covered area. Because our participants had to differentiate between two simultaneously presented stimuli, the lack of compensation most likely does not affect our psychophysical measures but might be important with respect to the comparison with other studies.35

We performed our experiments in separate blocks. During each block, we used a specific reference number stimulus (RN) ranging from 5 to 10 and contrasted this stimulus with a test number stimulus (TN) from RN-3 to RN + 3. The lower border of the range excluded the possibility that the task could be completed exclusively by subitzing, the upper border ensured that the task was not too difficult. The position of TN and RN (left or right display) was randomly chosen in each trial. The resulting seven configurations of TN and RN were repeated in a random order 6 times each resulting in a total of 42 trials for each block. The series of the blocks (i.e., the series of RNs) was determined by chance for each participant. Only once before the experiment, the participants were shown all possible combinations of RN and TN. The participants were not informed about the reference number of the actual block. They were instructed verbally to press the arrow key which was directed towards the perceived larger numerosities (two-alternative forced choice task).

### TABLE 1

Weekly gaming time in hours of preferred game genres of VGPs

| First person ego-shooter | Action/sport | Real-time strategy | Turn-based strategy | Non-action role play | Music | Other |
|-------------------------|--------------|--------------------|---------------------|----------------------|-------|-------|
| Weekly gaming time      | 6.2          | 3.6                | 4.6                 | 2.1                  | 4.5   | 1.8   | 2.1   |
Data analysis

The left and right key presses of the participant for each TN were transformed into percentage of larger reports of the TN compared to the RN. To quantify the ability of the participants to estimate numerosities objectively, we fitted the reports by a sigmoidal logistic function (Equation 1) shown in Figure 2B.

\[
f(x) = \frac{\alpha}{1 + e^{-(b+(kx))}}
\]

using lsqnonlin in MATLAB. This function allows the properties of the numerical sense of each participant to be determined objectively.

Although the participants performed a two-alternative forced choice task, it is possible to calculate the point of subjective equality (PSE) as the inflection point of Equation 1 from the fitted parameters \(\alpha\) (horizontal asymptote), \(b\) and \(k\) (exponential parameters) as indicated by Equation 2.

\[
PSE = -\frac{b}{k}
\]

The accuracy of the participants’ responses (ACC) can be determined by the difference between the PSE and the actual reference number (RN) in a given block.

In addition to the point of subjective equality (PSE), the logistic function sheds light into the sensory precision of the participants as well as the ability to differentiate stimuli. Steep functions at the PSE reflects high precision of the responses whereas shallow functions indicate low precision. Precision is determined by the ability to differentiate two numerosities as the just noticeable difference (JND). We define the JND as the difference between the ordinate corresponding 75% of the maximal response \(\alpha\) and the PSE. Although only integer numbers can be used in the experiments, the JND as a real number is a handle to the theoretical threshold which is needed to separate two numerosities for each participant. To inform about the probability density of our experimental data, we present our data as violin plots.

To examine the differences between VGPs and NVGPs, we build linear regression models (MATLAB function fitlm) upon the reference number RN (5 to 10) and video gaming (0: VGP, 1: NVGP) for PSE, ACC, and JND and report the outcome in tables. To document the validity of the linear regression models, we performed subsequently an analysis of variance (MATLAB function anova) and report the F and p values of the model and the residuals to the model-free variance (lack of fit). In addition, to address the influence of the individual amount of video-game duration (expressed as weekly gaming time), we built different linear regression models with the specific gaming times of each participant with subsequent ANOVA.

2.4 Data analysis

3 RESULTS

3.1 Data from a typical participant (VGP)

Before we focus on the differences between VGPs and NVGPs, we show the results from a typical participant from the cohort of VGPs. Figure 3A shows the result from an experimental block (42 trials) using 5 as RN, Figure 3B shows the outcome of a block with RN 7. In case of RN 5, this participant perfectly discriminated the larger dot-display for all TNs resulting in JND = 0.105. For RN 7, the participant reported erroneously once that TN 8 seems to be smaller than RN and once that TN 6 seems to be larger than RN. The remaining TNs were all correctly reported (JND = 0.650). From all experiments (RN 5 to 10) with this participant classified as VGP, the point of subjective equality (PSE), the accuracy (ACC) and the just noticeable difference (JND) were obtained as indicated in Figure 4A–C.
The participant responses displayed a high degree of accuracy. He was able to recover all RNs correctly indicated by the fact that the obtained PSE followed RN very closely ($R^2 = 0.984$, $F = 250.2$, $p < 0.001$). However, there were substantial differences in the response characteristics due to the different RNs. The accuracy drops slightly, but not significantly, with increasing RN ($R^2 = 0.588$, $F = 5.729$, $p = 0.074$). And there is a tendency that numerosities resolution expressed as JND increased with RN ($R^2 = 0.276$, $F = 1.531$, $p = 0.283$). We did not measure the response latencies of the participants.

### 3.2 Differences in numerosities estimations between VGPs and NVGPs

The point of subjective equality (PSE) provides a handle for the ability of the participants to recover the reference number in a given experimental block. Figure 5 shows the resulting distributions of PSE for all reference numbers (5 to 10) separated for the 32 VGPs and 34 NVGPs.

We calculated a linear regression model ($PSE \sim 1 + RN + PLAYER$) with the factors $RN$ (5 to 10) and video gaming (PLAYER, 0: VGP, 1: NVGP) on the PSE values shown in Table 2. The estimate of the factor $RN$ (0.984) is very close to unity which indicates that both groups were able to recover the numerosities. The estimate of video gaming (0.243) shows that NVGPs (coded as 1) tend to give slightly higher PSE values compared to VGPs (coded as 0). The linear regression model is valid (ANOVA, model: $F = 426$, $p < 0.0001$, residuals: $F = 1.245$, $p = 0.265$).
We also calculated a linear regression model on the accuracy of the participants' report defined as the difference between PSE and RN (ACC $\sim 1 + \text{RN} + \text{PLAYER}$). However, this linear model turned out to be not significant (adjusted R-squared 0.006, F-statistics vs. constant model $F = 2.33$, $p = 0.09$). So neither the size of the RN nor video-game play affected the accuracy significantly.

We analysed the participants' resolution to differentiate numerosities expressed as just noticeable difference (JND) shown in Figure 6. Small values of JND indicate superior numerosities resolution.

We build a linear regression model (JND $\sim 1 + \text{RN} + \text{PLAYER}$) whose parameter are shown in Table. 3. The linear regression model is valid (ANOVA, model: $F = 20.1$, $p < 0.0001$, residuals: $F = 0.2346$, $p = 0.98934$). JND increases significantly with RN (estimate of factor $\text{RN} 0.0967$), and VGP have smaller JNDs compared to NVGPs (estimate of factor $\text{PLAYER} 0.199$).

### 3.3 Correlation of the psychophysical parameters with weekly gaming time

Next, we asked whether the prior-described differences between VGP and NVGP were modulated by the time spent video gaming. Therefore, we calculated another linear regression models in which the categorical parameter PLAYER (0 or 1) was replaced by the individual weekly video gaming duration.

As Table 4 shows, the dependency of the factor RN on the point of subjective equality (PSE) was significant. However, the factor weekly video gaming duration did not influence the PSE significantly. PSE increases with a slope very close to unity (1.0047) with RN. The

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**TABLE 2** Linear regression model of PSE

| PSE $\sim 1 + \text{RN} + \text{PLAYER}$ |
|-----------------------------------------|
| Estimated coefficients:                |
| Estimate | SE   | tStat | p Value |
| Intercept: | $0.20876$ | $0.26674$ | $-0.78263$ | $0.43432$ |
| RN: | $0.98435$ | $0.033803$ | $29.12$ | $3.6326e-100$ |
| PLAYER: | $0.24348$ | $0.11551$ | $2.1078$ | $0.035681$ |
| Number of observations: 396, error degrees of freedom: 393 |
| Root-mean-square error: 1.15 |
| R-squared: 0.684, adjusted R-squared 0.683 |
| F-statistic versus constant model: 426, p value = 3.7e-99 |

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The linear regression model is valid (ANOVA, model: $F = 421, p < 0.0001$). We also calculated a linear regression model on the accuracy of the responses ($ACC \sim 1 + RN + Duration$). However, this model turned out to be not significant (adjusted $R^2 = 0.001$, $F$-statistics vs. constant model $p = 0.454$).

Table 5 shows the linear regression model on JND. The influences of $RN$ as well as weekly gaming duration are significant. The resolution of the participants’ responses increased significantly with $RN$, but decreased significantly with the weekly gaming duration. The linear regression model is valid (ANOVA, model: $F = 18.361, p < 0.0001$, residuals: $F = 1.2627, p = 0.15456$) (Figure 7).

4 | DISCUSSION

We examined the ability of VGPs and NVGPs to estimate the number of items in a visual display. We found no difference in the accuracy between VGPs and NVGPs. However, the sensory precision expressed as just-noticeable difference (JND) on one hand decreased with increasing numerosities. On the other, VGPs showed a higher sensory precision and therefore better numerosities resolution compared to NVGPs.

4.1 | Motivation as explanation in general

A general problem in cross-sectional studies comparing the abilities of VGPs with NVGPs is the potentially differential motivation of the cohorts. It is easy to see that VGPs are higher motivated as earlier explained. So it is mandatory to keep the purpose of the study hidden during the recruitment of participants was well as during the execution of the experiments as we did in our study. In addition, it is important to note that we did not observe a difference in the weekly sporting times between VGPs and NVGPs. This excludes the rather general explanation that the superiority of VGPs in numerical

| TABLE 3  | Linear regression model of JND |
|-----------|-------------------------------|
| $JND \sim 1 + RN + PLAYER$ |
| Estimated coefficients: |
| Estimate | SE | tStat | p Value |
| Intercept | $-0.084192$ | $0.14025$ | $-0.6003$ | $0.54865$ |
| $RN$ | $0.096707$ | $0.017774$ | $5.441$ | $9.34e-08$ |
| PLAYER | $0.1995$ | $0.060737$ | $3.2846$ | $0.001128$ |
| Number of observations: 396, error degrees of freedom: 393 |
| Root-mean-square error: 0.604 |
| R-squared: 0.0932, adjusted R-squared 0.0886 |
| $F$-statistic versus constant model: 20.2, $p$ value = 4.48e–09 |

| TABLE 4  | Linear regression model of PSE |
|-----------|-------------------------------|
| $PSE \sim 1 + RN + duration$ |
| Estimated coefficients: |
| Estimate | SE | tStat | p Value |
| Intercept | $-0.18262$ | $0.27446$ | $-0.66539$ | $0.50619$ |
| $RN$ | $1.0047$ | $0.038113$ | $26.36$ | $6.499e-89$ |
| Duration | $-0.008077$ | $0.0068996$ | $-1.1708$ | $0.24241$ |
| Number of observations: 396, error degrees of freedom: 393 |
| Root-mean-square error: 1.15 |
| R-squared: 0.682, adjusted R-squared 0.68 |
| $F$-statistic versus constant model: 421, $p$ value = 1.7e–98 |

| TABLE 5  | Linear regression model of JND |
|-----------|-------------------------------|
| $JND \sim 1 + RN + duration$ |
| Estimated coefficients: |
| Estimate | SE | tStat | p Value |
| Intercept | $-0.10252$ | $0.14436$ | $-0.71017$ | $0.47802$ |
| $RN$ | $0.12148$ | $0.020047$ | $6.0597$ | $3.19e-09$ |
| Duration | $-0.009852$ | $0.0036292$ | $-2.7147$ | $0.00692$ |
| Number of observations: 396, error degrees of freedom: 393 |
| Root-mean-square error: 0.607 |
| R-squared: 0.0855, adjusted R-squared 0.0808 |
| $F$-statistic versus constant model: 18.4, $p$ value = 2.38e–08 |

Note: Estimate = coefficient estimates, SE = standard error of the coefficients, tStat = t-statistics for each coefficient to test the null hypothesis (coefficient is equal to 0), p Value = resulting from tStat for each coefficient.
processing might be related to a higher activity state of VGPs in several daily live situations.

### 4.2 Number processing in the human brain

Before possible differences between VGPs and NVGPs can be addressed, we like to describe the neuronal substrate of number processing in the human brain. An early PET study revealed activation in superior and inferior frontal gyri as well as inferior parietal lobe in subjects performing a simple mathematical task. Using the fMRI adaptation protocol, tuning curves for numerosities were shown in the intraparietal sulcus (IPS). This adaptation protocol made it possible to reveal non-symbolic numerosities representation in the IPS and the lateral PFC. Areas in the intraparietal sulcus IPS and superior parietal lobule are activated when numerical information is processed. High resolution enabled by high field fMRI approach, map of numerosities were shown in the superior parietal lobule. In the frontal and parietal lobe, maps independent of modality have been shown. Finally, by means of single-unit recordings in neurosurgical patients, numerosities selective neurons have been sown in the medial temporal lobe (MTL). It should not be neglected that there is also pre-attentive processing of numerical visual information expressed in the visual mismatch negativity (vMMN) recorded from parieto-occipital electrodes.

### 4.3 differences between VGPs and NVGPs:

Green and Bavelier suggested that the enhancement of VGPs is not related to the fast process called subitizing underlying the processing of small numbers. This is rather trivial because neither VGPs nor NVGPs show errors for small numbers. So the difference between VGPs and NVGPs remains to the slower process acquiring larger numerosities called ANS. It is less likely that video-game play causes specific and exclusive changes in the brain areas underlying the processing of numerosities as explained above. As emphasised in Section 1, playing video games appears to improve cognition beyond numerical cognition. As different the experimental tasks are, in which differences between VGPs and NVGPs have been reported, a common denominator is that attentional mechanisms are involved.

It is widely accepted to separate a dorsal and ventral attention system: the dorsal system consists mainly in the intraparietal sulcus (IPS) and frontal eye field (FEF), whereas the ventral system consists mainly in the temporo-parietal junction (TPJ) and the ventral frontal cortex (VFC). The differences between VGPs and NVGPs are more likely in top-down attentional processes represented in the dorsal attention network. The exogenous forms of attention in the ventral processing stream are less likely to be different between VGPs and NVGPs. This notion is supported by the finding that the response to task irrelevant distractors in visual-evoked potentials (VEP) is more pronounced in NVGPs compared to VGPs. Suppression of irrelevant information from being processed is one of the key elements of attentional mechanisms. In addition, the reduction of the responses elicited by the distractors is greater in potentials generated in the parietal cortex compared to the occipital cortex and an increased suppression of steady-state visual-evoked potentials to unattended peripheral sequences in VGPs compared to NVGPs was found.

Although the explanation of the differences between VGPs and NVGPs rooted in the attentional systems is quite plausible, there are alternative explanations for these differences: Firstly, it was earlier suggested that a possible superiority of VGPs in enumeration tasks may be related to increased visual working memory or, alternatively, faster cycling through memory. However, our data rule out a possible influence of working memory, we presented the stimuli simultaneously and very brief (200 ms only). So working memory seems not to be involved in our experimental setting with a slight exception explained below. In addition, the possible assumption that VGPs have a greater speed of shifting attention (facilitates the process of counting the items) is at odds with our previous findings addressing the speed of attention shifts. Secondly, Because our number stimuli were not balanced for visual cues such as covered area, cue density or luminance, VGPs might be better because of their superior perception. Similarly, because we did not use backward masking, the better numerosities estimation of VGPs might be indeed explained by their better working memory. Thirdly, psychophysical data reflect the output of two processes in general: on one hand, there is a given sensory precision and accuracy of the subject, here with respect of number representation. On the other, there is always a decision process underlying the response of the participants, independent of the actual modality. Recently, it was argued based on two behavioural experiments and a mathematical model that the precision of the numerical representation is not the main driver of the behaviour, instead general decision-making processes drive the observed performance. Because VGPs showed improved probabilistic inference, the reported differences might solely be due to differences in the decision-making process. So it remains for future studies, especially training studies, to document the causal relation between video-game play and processing of numerosities.

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**CONFLICT OF INTEREST**

The authors declare no conflict of interest.

**AUTHOR CONTRIBUTIONS**

JS and UI designed the study, interpreted the data and wrote the manuscript together. UI wrote the Matlab scripts for data acquisition
and analysis. JS tested the participants. JS and UI revised together the initial manuscript.

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**ENDNOTE**

* https://icd.who.int/browse11/l-m/en#http%3a%2f%2fid.who.int%2ficd

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Additional supporting information may be found online in the Supporting Information section at the end of this article.

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