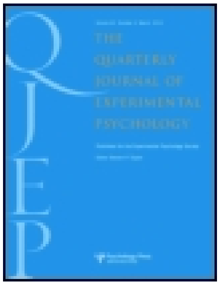

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Differentiating two- from three-dimensional mental rotation training effects

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Differentiating two- from three-dimensional mental rotation training effects

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Block videogame training has consistently demonstrated transfer effects to mental rotation tasks, yet how variations in training influence performance with different stimuli remains unclear. In this study, participants took mental rotation assessments before and after a 3-week training programme based on 2D or 3D block videogames. Assessments varied in terms of dimensionality (2D or 3D) and stimulus type (polygon or body). Increases in videogame scores throughout training were correlated with mental rotation improvements. In particular, 2D training led to improvements in 2D tasks, whereas 3D training led to improvements in both 2D and 3D tasks. This effect did not depend on stimulus type, demonstrating that training can transfer to different stimuli of identical dimensionality. Interestingly, traditional gender differences in 3D mental rotation tasks vanished after 3D videogame training, highlighting the malleability of mental rotation ability given adequate training. These findings emphasize the influence of dimensionality in transfer effects and offer promising perspectives to reduce differences in mental rotation via designed training programmes.

Keywords: Mental rotation; Stimulus dimensionality; Gender differences; Transfer; Videogame training.

Spatial reasoning represents a critical component to solve diverse problems, from simple everyday tasks, such as visualizing spatial configurations or finding one's way, to more complex problems in fields ranging from mechanical engineering and science to music and motor activities. As a result, an extensive body of literature has identified numerous occupations related to higher spatial ability (see, for a review, Hegarty & Waller, 2005), paving the way to effective training programmes. Recently, the prevalence of spatial reasoning in myriad of professional disciplines has prompted many educational institutions to incorporate classes emphasizing spatial ability in traditional curricula (Moreau, 2012a; Newcombe & Frick, 2010).

Within spatial ability, mental rotation is at the core of numerous studies since the pioneer experiments of Shepard and colleagues (Cooper & Shepard, 1975; Shepard & Metzler, 1971). Higher mental rotation ability has been linked to science curricula (Moreau, Mansy-Dannay, Clerc, & Guerrien, 2010; Peters, Lehmann, Takahira, Takeuchi, & Jordan, 2006), videogame playing (Boot, Kramer, Simons, Fabiani, & Gratton, 2008; Feng, Spence, & Pratt, 2007), musical

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practice (Brochard, Dufour, & Despres, 2004), or motor skill training (Jansen, Titze, & Heil, 2009; Moreau, Clerc, Mansy-Dannay, & Guerrien, 2012; Pietsch & Jansen, 2012). The versatility of activities that require the ability to visualize dynamic spatial properties underscores the importance of mental rotation in human cognition.

Corroborating evidence comes from intervention research. Training studies have demonstrated reliable effects on mental rotation performance (Lohman & Nichols, 1990), with numerous implications (see, for a review, Uttal et al., in press). For example, the well-documented gender difference in mental rotation (Voyer, Voyer, & Bryden, 1995) can be reduced or completely erased with training, underlining the malleability of individual differences in spatial tasks (Kail & Park, 1990). However, the specific factors mediating changes over time are still unclear. In particular, a study by Heil and colleagues showed mental rotation improvements restricted to practice trial settings, after four sessions of training (Heil, Rösler, Link, & Bajric, 1998). Training specificity is further supported by corroborating evidence showing improvements specific to stimulus orientations encountered in practice blocks (Sims & Mayer, 2002; Tarr & Pinker, 1989). Together, these findings suggest limited training-induced improvements in mental rotation, with rare transfer to different stimuli or conditions.

Despite the elusiveness of transfer, it is worth noting that the studies mentioned above used exclusively paper-and-pencil training tasks. Considering the critical role of dynamic experiences to generalize spatial ability improvements (Moreau, 2012b), the use of paper-and-pencil tasks, which lack physical manipulations, could explain restricted effects. In contrast, complementary experiments have assessed the effect of computerized training. These are often based on popular block videogames such as Tetris or its 3D counterpart, Blockout, and have shown reliable transfer to paper-and-pencil mental rotation tasks (De Lisi & Cammarano, 1996; Okagaki & Frensch, 1994). A study by Wright and colleagues confirmed theses findings, showing mental rotation improvements after computerized practice independent of stimulus type (Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008).

What features of videogame training can account for general mental rotation improvements, considering that paper-and-pencil training have systematically failed to show transfer effects? Beyond increased control over important factors such as scores, improvements, and stimulus types and occurrences, videogames have interesting implications in terms of training characteristics. They allow dynamic and active interactions with stimuli, a factor that might mediate wide and general changes. In line with this idea, studies have pointed out similarities between manual rotation and virtual rotation (Ruddle & Jones, 2001), thus emphasizing the pertinence of virtual environments for real-life applications (Waller, 2000). Consistent with research showing the effect of haptic experiences on mental simulation (White, 2012), transfer might depend on active manipulation in an egocentric referential through physical or virtual interactions (Janczyk, Pfister, Crognale, & Kunde, 2012), a lacking component of paper-and-pencil training. Therefore, the dynamic features of block videogames might be underlining their efficacy to train mental rotation, as suggested by recent research on the relation between higher cognition and the motor system.

As such, further evidence comes from work showing the involvement of motor processes in mental rotation (Amorim, Isableu, & Jarraya, 2006; Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998; Wraga, Thompson, Alpert, & Kosslyn, 2003). Although mental rotation usually relies on visual working memory (Hyun & Luck, 2007), this mechanism seems to be malleable with experience. This idea is in line with Logie's distinction between the visual cache, a passive store holding information about colour and form, and the inner scribe, an active rehearsal component dealing with spatial relations and movement (Logie, 2011; Logie & Pearson, 1997). In particular, sensorimotor interactions with the environment influence the processes favoured to perform mental rotation (Steggemann, Engbert, & Weigelt, 2011): Greater experience results in a shift from visual to motor strategies (Moreau, 2012b), triggering improvements across a diverse range of stimuli (Moreau, Mansy-Dannay, Clerc, & Guerrien, 2011). In a similar vein, it is possible that active manipulations inherent to block videogame playing could allow general alterations transferable to different stimuli. Block videogame training might facilitate the transition from visual to motor processes in mental rotation, whereas paper-and-pencil training might induce more limited changes. This experience-based mechanism could explain discrepancies concerning the system responsible for storage in mental rotation (Liesefeld & Zimmer, in press) and differences in transfer effects between paper-and-pencil and videogame training.

Although potentially promising, training studies based on block videogames have yet to provide definite answers to several critical issues. In particular, there has been a lack of standardized procedures to compare the effects of different training programmes on spatial ability tasks. Therefore, questions remain concerning the distinction between 2D and 3D mental rotation training effects—that is, what consequences specific training regimens have on mental rotation of different stimuli. This is of particular importance as 2D and 3D mental rotation processes have clearly been distinguished based on distinct neural correlates (Kawamichi, Kikuchi, Noriuchi, Senoo, & Ueno, 2007) and on neuropsychological evidence (Turnbull, Driver, & McCarthy, 2004). Since mental rotation of 2D stimuli and 3D stimuli require different processes, training improvements might not transfer from one type of stimuli to the other. In this case, however, the usual generalization of mental rotation as a generic ability, regardless of dimensionality, is dangerously misleading.

In 2D mental rotation, all transformations are constrained within a single plane. This means that figure elements are never occluded, allowing mental simulation without the need for spatial inferences based on incomplete information. Tasks typically require straightforward similarity judgements. Although analogous problems are involved in 3D mental rotation tasks, additional information about depth has to be extracted from 2D depictions, with consequences on task difficulty as well as on the underlying processes. Beyond the need to preserve geometrical properties while the figure is being rotated, individuals have to maintain 3D spatial layouts from prior visual exploration of 2D depictions. The transformation from a 2D to a 3D mental representation, "dimensionality crossing", is responsible for the large gender effect favouring males in most 3D mental rotation designs (Voyer et al., 1995). Consistent with this idea, 3D mental rotation using virtual reality paradigms, which do not require dimensionality crossing, does not yield gender differences in performance (Parsons et al., 2004).

Taken together, these findings suggest that the cognitive load required by dimensionality crossing, rather than the process of mental rotation itself, might be responsible for gender differences. In other words, gender differences do not seem to be a consequence of mental rotation ability per se, but of the capacity to extract spatial properties from a stimulus for further manipulation. Therefore, training emphasizing dimensionality crossing in addition to mere mental rotation, such as 3D mental rotation training, should result in significant improvements regardless of stimuli. In contrast, training that does not emphasize dimensionality crossing, such as 2D mental rotation training, should lead to improvements in 2D but not in 3D mental rotation tasks.

The aim of the present study was twofold. The primary objective was to assess the effects of 2D and 3D mental rotation training programmes on mental rotation ability. The experimental apparatus consisted of training tasks with geometric figures only and of mental rotation assessments with either similar or different stimuli, to determine the extent to which training in a specific condition (2D or 3D) transfers across different stimuli. A benefit from 3D training on all mental rotation assessments was expected, along with an effect of 2D training restricted to 2D assessments. Because gender differences are preponderant in mental rotation, an additional objective was to assess differential effects of training in women and men.

To explore these questions, participants trained either on a 2D or a 3D block videogame. Before and after training, they were tested on mental rotation tasks composed of either polygon or body items, each in a 2D and a 3D version. Therefore, stimulus types were manipulated in two different aspects, object and dimensionality, for a total of four assessment tasks.

Method

Participants

Forty-eight university students were recruited to participate in the study, via flyers posted on campus. They were all right-handed, as determined by the Hand Preference Test (Annett, 1970). Two of them were excluded after pretest assessments because they did not score above chance (<50% accuracy). Therefore, 46 participants took part in the training (22 males, 24 females; mean age, $M = 20.52$ years, $SD = 2.10$). They were not rewarded monetarily, but were told that training would improve mental rotation, an ability presented in the advertising flyer as critical in numerous academic and professional activities. All participants gave informed consent, and the study was conducted in accordance with the American Psychological Association Ethical Guidelines and with the Helsinki Declaration of 1975.

None of the participants had extensive experience playing videogames, defined as weekly practice of a particular game. This was assessed via a questionnaire administered prior to the experiment. Men and women were randomly assigned to one of the two following conditions: (a) 2D block videogame training and (b) 3D block videogame training. Thus, gender was balanced across conditions. Over the course of the experiment, participants were asked not to practise the training games or any other videogames outside the testing room. This factor was controlled via a self-report questionnaire at the end of the experiment.

Videogame training

Design. Participants underwent three weeks of training in a computer lab, with the first and the last day dedicated to mental rotation assessments. The training period included 16 sessions of 45 min each, for a total of 12 hours of practice. Participants trained every day of the week except Sundays. The 2D group trained on Tetris, whereas the 3D group trained on Blockout. Developed by California Dreams, Blockout is a game fundamentally similar to Tetris, the substantial difference being the possibility to rotate geometric shapes in depth (see Figure 1). In Blockout, rows are built in a 3D array, with pieces moving away from the player. Array dimensions were 12×18 squares in Tetris and $5 \times 5 \times 12$ squares in Blockout. Daily average performance was recorded every five training days (Days 1, 6, 11, and 16), to provide score trends for each participant.

Procedure. In both videogames, the entire set of pieces was composed of eight different shapes. The frequency of each piece was randomized throughout training trials. Difficulty increased over time via incremental piece falling speed. Completion of a layer resulted in the automatic deletion of the pieces involved, therefore clearing space at the bottom of the playing area. The game ended when the pieces were stacked up to the top of the playing area. The goal of Tetris and Blockout was to complete as many layers as possible. The “piece preview” command, which allows predicting of upcoming pieces, was deactivated throughout the entire training period.

Scoring. Scoring procedures were matched in both videogames. Each piece started with a score value, which increased linearly at each successive level. Every time a piece was rotated or translated, its value decreased. Dropping a piece resulted in a score proportional to the distance it fell. Therefore, highest scores could be achieved by dropping pieces immediately from the start, without rotation or translation. In practice, however, this would result in a nonoptimal pile of pieces, detrimental to overall performance. Participants were verbally made aware of all of the scoring parameters mentioned above.

Scoring took into account the overall number of complete layers built, with a bonus depending on the number of layers built at once (1 layer = 100 points, 2 layers = 200 points, 3 layers = 400

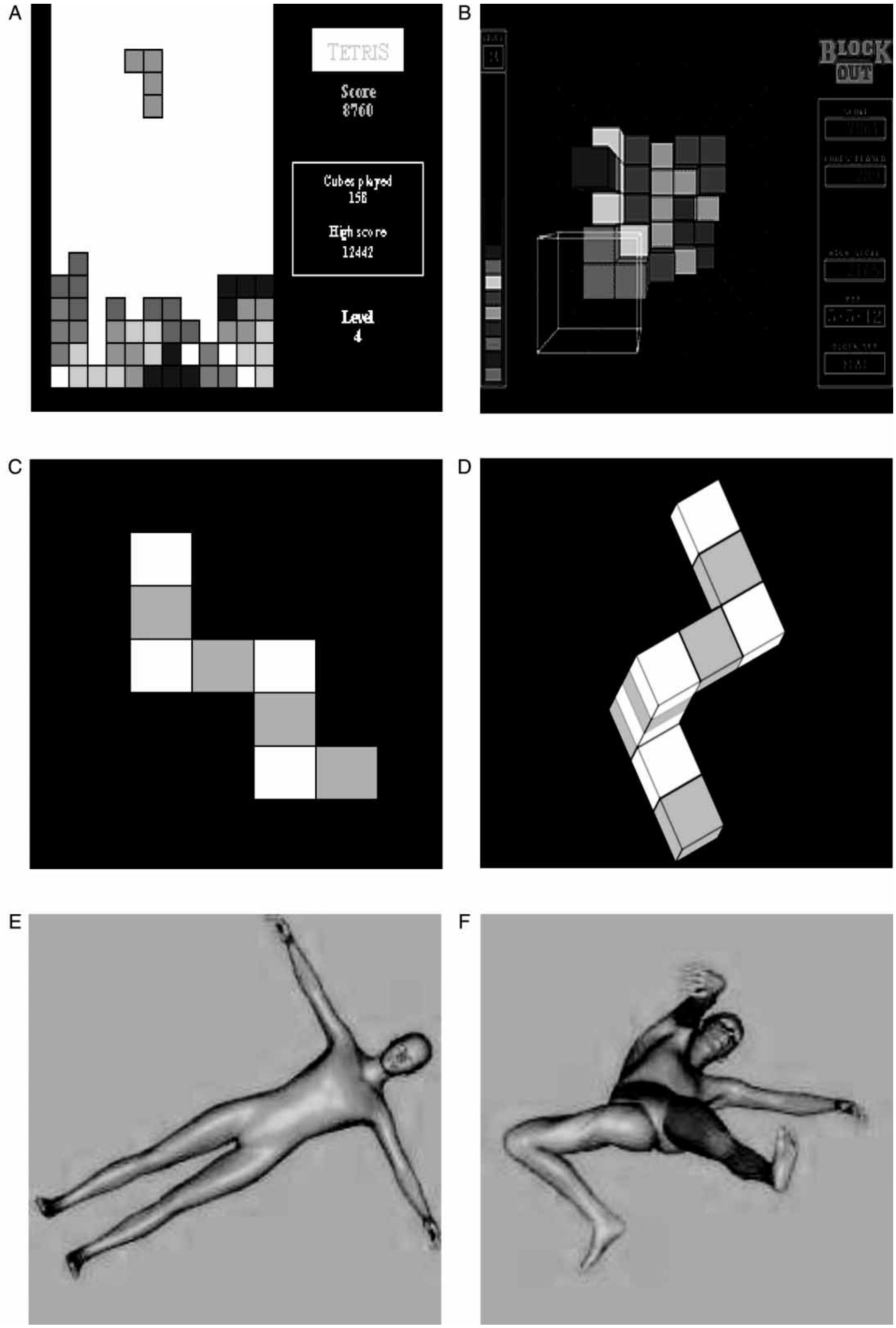

Figure 1. *Example stimuli from Tetris and Blockout training games (A–B), polygon 2D and 3D tasks (C–D), and body 2D and 3D tasks (E–F). To view a colour version of this figure, please see the online issue of the Journal.*

points). At the onset of training, participants were explicitly instructed that delaying layer completion, rather than building layers one at a time, was rewarded with bonus points. They were also told that an additional bonus was awarded every time the playing area was empty (200 points bonus).

This elaborate scoring procedure is the one used in competitive block videogame playing. It allows rewarding of the ability to mentally predict the rotation of a piece, as opposed to its constant manipulation. Therefore, highest scorers are those who can visualize rotations quickly and accurately. In contrast, individuals who rely on actual rotations rather than on predictions get lower scores, as unnecessary rotations lead to losses in terms of piece value. To provide a challenging version of the videogames to all participants, average scores were saved at the end of each training session. On the following day, each participant started at the average level of the previous trial session. This ensured that game levels were automatically adjusted to each participant, a feature that has proven critical in cognitive training (Shipstead, Redick, & Engle, 2012).

Mental rotation assessments

Design. Before and after training, participants took mental rotation assessments (see Figure 1). Four tasks were designed, with variations concerning item type (polygon vs. body) and item dimensionality (2D vs. 3D). The polygon tasks were based on Shepard and Metzler original stimuli (Shepard & Metzler, 1971) and were redrawn from the Mental Rotation Stimulus Library (Peters & Battista, 2008). The body tasks were created with DAZ Studio 4 (DAZ Productions, Inc.). The 2D tasks involved rotations in a single plane (x, y), whereas the 3D tasks included combinations of rotations in the three axes (x, y, z).

Procedure. All tasks ran on E-prime 2.0 (©Psychology Software Tools, Inc., 2010). Fifty pairs of items were presented in each task. In all cases, a target figure, on the left of the screen, was presented at a random orientation, whereas the figure on the right was either a match (50% of the trials) or a mirror-image (50% of the trials) rotated by 45°, 90°, 135°, or 180°.

Participants had to make a match/no-match decision via two response keys on the keyboard. They answered by pressing a key with their right index (match) or right middle finger (no match). Stimuli were presented until a key was pressed and were followed by a blank screen. Participants were asked to focus on accuracy and speed.

Scoring. Accuracy and response time (RT) were recorded for each trial. One point was awarded for each correct answer, whereas no points were subtracted for incorrect answers. Therefore, scores in each task could range from 0 to 50.

Results

Results concerning videogame practice effects are presented below, followed by transfer effects to mental rotation assessments.

Practice effects

I report here a 2 (gender) × 2 (training type) × 4 (training duration) mixed factorial analysis of variance (ANOVA) with repeated measures on the last variable. Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(5) = 85.57$, $p < .001$, and therefore the initial degrees of freedom were corrected using the Greenhouse–Geisser estimates of sphericity for all repeated measures ($\varepsilon = .46$). The p-values reflect these changes.

Unsurprisingly, the analysis showed a main effect of training duration on videogame performance, $F(1.39, 58.38) = 790.37$, $p < .001$, $\eta_p^2 = .95$ —that is, practice led to improvements in the trained tasks. Pairwise comparisons with Bonferroni correction showed improvements from any testing day to the next regardless of training type (Tetris or Blockout). The analysis also revealed a main effect of gender, $F(1, 42) = 6.72$, $p < .05$, $\eta_p^2 = .14$, men outperforming women, and of training type, $F(1, 42) = 19.30$, $p < .001$, $\eta_p^2 = .31$, with higher overall scores in Tetris than in Blockout throughout the training period. Moreover, the interaction between training duration and training

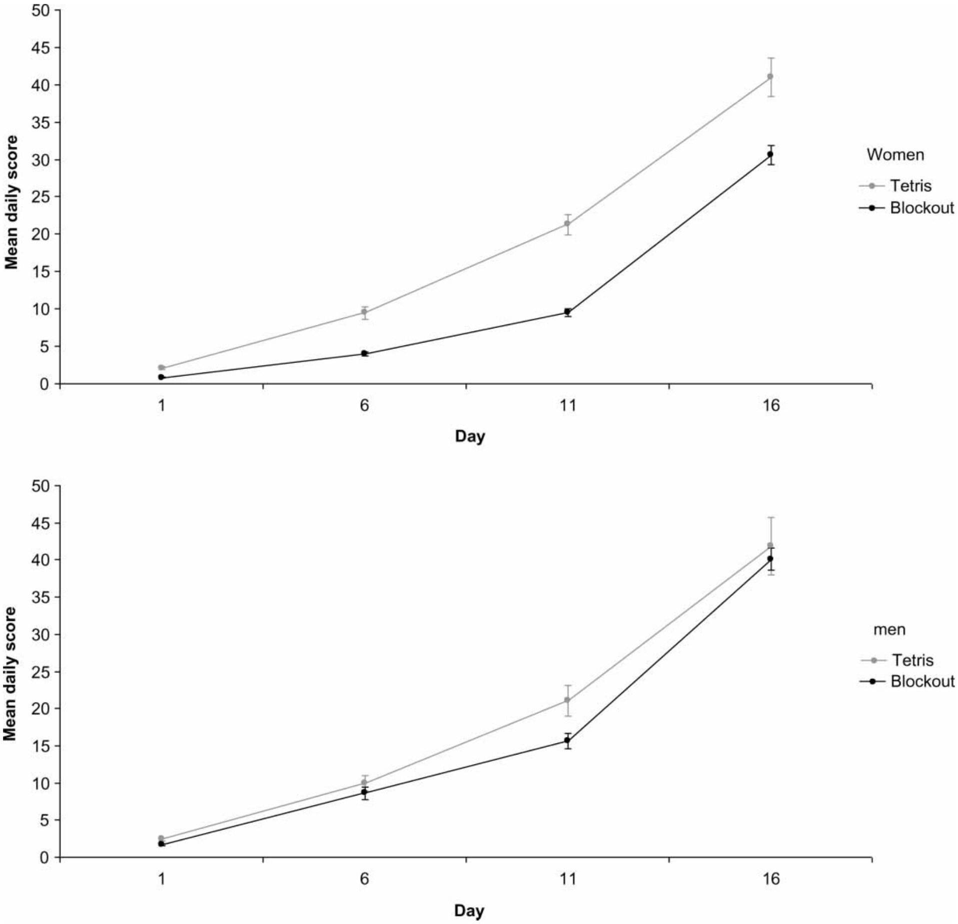

Figure 2. *Videogame mean performance (in thousand points) on Days 1, 6, 11, and 16, for women (top) and men (bottom). Bars represent standard errors of the means.*

type was significant, $F(1.39, 58.38) = 8.27$, $p < .001$, $\eta_p^2 = .16$, since Tetris training led to greater improvements than Blockout training. Pairwise comparisons with Bonferroni correction showed this effect for Day 11 and Day 16 but not for Day 1 and Day 6. This effect was not an artefact of videogame scoring, as the maximum points awarded as a function of time did not differ from one game to the other.

The interaction between training duration and gender was significant, $F(1.39, 58.38) = 2.77$, $p < .05$, $\eta_p^2 = .06$. Post hoc analyses showed larger overall improvements for men than for women (Tukey's HSD $< .05$), despite similar performances on Day 1, Day 6, and Day 11. In addition, there was an interaction between gender and training type, $F(1, 42) = 5.16$, $p < .05$, $\eta_p^2 = .11$. Post hoc analyses showed that women had lower scores than men over the entire Blockout training period (Tukey's HSD $< .05$, in all cases), but there was no gender difference at any point of Tetris training (Tukey's HSD $> .05$, in all cases). Thus, men outperformed women in Blockout throughout training, but women and men showed comparable performance at all measurement points in the Tetris condition (see Figure 2). Interestingly, gender differences increased throughout training in the Blockout condition, more specifically from

Day 1 to Day 6 and from Day 11 to Day 16 (Tukey's HSD < .05, in both cases). Therefore, men showed larger increases in scores than women over the 3-week training programme.

Transfer effects

Separate 2 (gender) × 2 (training type) × 2 (test session) mixed factorial ANOVAs with repeated measures on the last variable were conducted for each mental rotation task, to reveal transfer effects from videogame training to mental rotation tasks (see Figure 3). For all analyses on RTs, outliers (<5%) containing RTs above or below 2.5 standard deviations for the corresponding mean cell value were excluded from the analyses. Table 1 presents RT means and standard deviations for all tasks.

In 2D tasks, the analyses on accuracy revealed significant main effects of test session (pretest vs. posttest) on both stimulus types [polygon: $F(1, 42) = 107.74$, $p < .001$, $\eta_p^2 = .72$; body: $F(1, 42) = 73.75$, $p < .001$, $\eta_p^2 = .64$], indicating improvements from pretest [polygon: $M = 38.8$, $SD = 2.86$, body: $M = 39.6$, $SD = 2.97$] to posttest [polygon: $M = 41.7$, $SD = 2.75$, body: $M = 42.4$, $SD = 2.92$]. However, no significant effect of gender or training type was found, underlining comparable 2D mental rotation accuracy for men and women, before or after Tetris and Blockout training, and comparable efficacy of the two training conditions on 2D mental rotation performance. Analyses on RTs yielded partly consistent results, with main effects of test session on both stimulus types [polygon: $F(1, 42) = 45.65$, $p < .001$, $\eta_p^2 = .48$; body: $F(1, 42) = 39.78$, $p < .001$, $\eta_p^2 = .42$], but no additional effect.

In 3D tasks, the analyses on accuracy yielded two 3-way interactions among training type, gender, and test session, for both stimulus types [polygon: $F(1, 42) = 11.29$, $p = .002$, $\eta_p^2 = .21$; body: $F(1, 42) = 5.36$, $p = .026$, $\eta_p^2 = .11$]. Simple interaction analyses revealed an interaction between gender and test session for the Blockout group [polygon: $F(1, 42) = 13.27$, $p = .001$, $\eta_p^2 = .39$; body: $F(1, 42) = 7.17$, $p = .014$, $\eta_p^2 = .25$] but not for the Tetris group. Pairwise comparisons with Bonferroni correction were conducted to determine the effect of test session for women and men. As predicted, 3D mental rotation accuracy improved with Blockout training (see Figure 3). Although accuracy differed significantly from women to men prior to training, no gender differences in any of the 3D tasks were found after training. Analyses on RTs were partly consistent with these findings, with a main effect of test session on RTs [polygon: $F(1, 42) = 15.20$, $p < .01$, $\eta_p^2 = .18$; body: $F(1, 42) = 19.76$, $p < .01$, $\eta_p^2 = .24$], but no effect of training type or gender.

Correlation analyses comparing pre- and posttest assessments were subsequently conducted to complement these findings. Although the sample was small for such analyses, correlations provide an interesting insight into the underlying similarities and differences between tasks. As expected, similar tasks in terms of dimensionality but with different stimuli (2D polygon and 2D body; 3D polygon and 3D body) were highly correlated [pre: $r(44) = .91$ and $r(44) = .76$, post: $r(44) = .87$ and $r(44) = .78$, respectively, all ps $< .05$], whereas tasks with similar stimuli but different dimensionality (2D vs. 3D) were not [pre: $r(44) = .10$ and $r(44) = -.02$, post: $r(44) = .12$ and $r(44) = -.05$, respectively, all ps $< .05$], suggesting separate processes underlying 2D and 3D mental manipulation, regardless of stimuli. The correlation matrix including the respective coefficients is presented in Table 2.

Because no control group was used, mental rotation improvements could be due to simple test–retest effects. In order to confirm that improvements in the videogames were related to gains in mental rotation, additional correlation analyses were conducted, taking into account improvements in videogame scores from the first to the last day of training and pretest to posttest changes. In the Tetris group, videogame improvements were significantly correlated to gains in both 2D mental rotation tasks [$r(21) = .66$, $p < .05$ and $r(21) = .43$, $p < .05$, respectively for polygon and body tasks], but were not correlated to gains in 3D mental rotation tasks. In contrast, videogame improvements in the Blockout group were significantly correlated to gains in both 3D mental

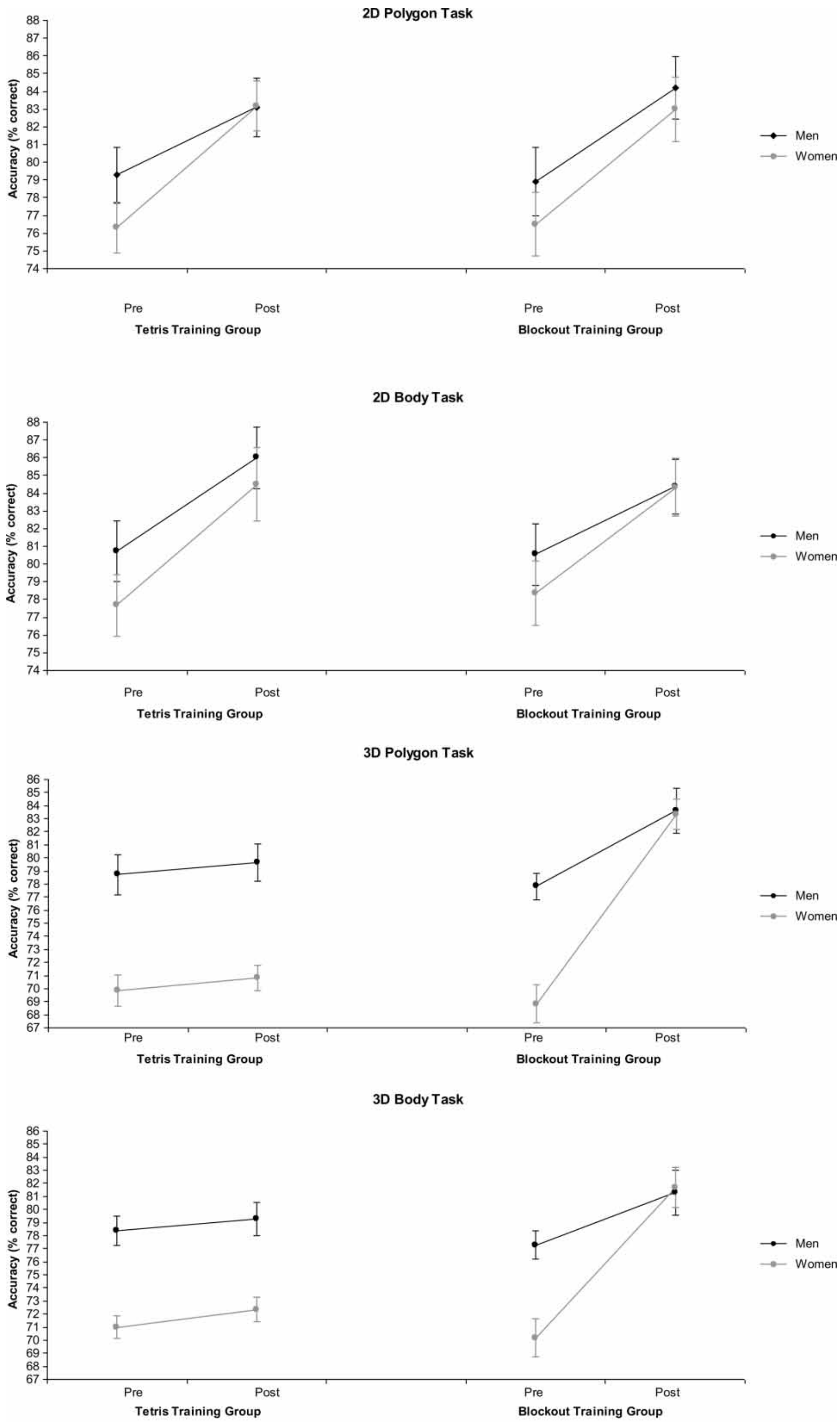

Figure 3. *Response accuracy for all mental rotation assessment tasks before and after training. Bars represent standard errors of the means.*

Table 1. *Mean response times in all assessment tasks for Tetris and Blockout groups, before and after block videogame training*

	Polygon		*Body*	
Training Type	*2D*	*3D*	*2D*	*3D*
Pretest				
Tetris	1376 (83)	1498 (124)	1385 (99)	1475 (88)
Blockout	1370 (87)	1506 (95)	1378 (95)	1458 (110)
Posttest				
Tetris	1153 (83)	1279 (115)	1195 (92)	1224 (92)
Blockout	1159 (78)	1227 (102)	1176 (90)	1178 (96)

Note: Response times in ms. Standard errors in parentheses.

Table 2. *Pearson* r *correlations, means, and standard deviations for all pre- and post-mental-rotation assessments*

Measure	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	M	SD
1. Pre 2D polygon	—								38.8	2.86
2. Pre 2D body	.91*	—							39.6	2.97
3. Pre 3D polygon	.10	.14	—						36.8	3.13
4. Pre 3D body	−.04	−.02	.87*	—					37.0	2.65
5. Post 2D polygon	.78*	.76*	.03	−.06	—				41.7	2.75
6. Post 2D body	.63*	.73*	.00	−.15	.76*	—			42.4	2.93
7. Post 3D polygon	.11	.18	.43*	.31*	.12	.00	—		39.6	3.43
8. Post 3D body	−.08	−.02	.30*	.31*	−.01	−.05	.78*	—	39.3	2.98

*$p < .05$, two-tailed.

rotation tasks [$r(21) = .49$, $p < .05$, and $r(21) = .54$, $p < .05$, respectively for polygon and body tasks] and in both 2D mental rotation tasks [$r(21) = .42$, $p < .05$, and $r(21) = .46$, $p < .05$, respectively for polygon and body tasks]. Together, these findings suggest a relation between training type and mental rotation improvements, the magnitude of the latter varying with increases in videogame scores.

Discussion

The aim of this study was to differentiate the effects of 2D and 3D block videogame training on mental rotation performance, along with providing a clearer understanding of gender differences in training and mental rotation transfer. To that purpose, participants took 2D and 3D mental rotation assessments, before and after a 3-week training programme based on block videogames. Mental rotation tasks varied both in terms of dimensionality (2D or 3D) and in terms of stimulus type (polygon or body).

Practice effects

Training led to improvements in videogame performance, regardless of gender or training type. However, participants training with Tetris and Blockout showed different score progressions, probably due to different levels of difficulty in the videogames. Compared with Tetris, Blockout requires more complex mental transformations, with a more diverse set of keys to play, which takes time to master adequately. The scoring procedure rewarded accurate predictions and penalized unnecessary rotations and translations, a factor that may account for differences in scores throughout training in Tetris and Blockout.

Gender differences in training were particularly informative. As expected from a substantial amount of literature showing gender differences in mental rotation (see for meta-analytic reviews, Linn & Petersen, 1985; Voyer et al., 1995), men outperformed women in videogame training. However, this effect was found in Blockout 3D training but not in Tetris 2D training. This finding corroborates previous research underlining the importance of dimensionality crossing to explain gender differences in mental rotation (Voyer et al., 1995).

Interaction effects complement these findings. Consistent with the idea of different levels of difficulty for Tetris and Blockout, training with the former led to larger increases in game scores than did training with the latter. Men showed larger improvements than women throughout training, although this effect was restricted to Blockout training. We shall see hereafter that gender differences in mental rotation assessments followed a different trend over time.

Transfer effects

In accordance with previous research on computerized mental rotation training (De Lisi & Cammarano, 1996; Terlecki, Newcombe, & Little, 2008), improvements from pre- to posttest assessments were significant across gender and training type. More specifically, training with a particular stimulus led to transfer across stimulus types, given that dimensionality was identical. This finding is in line with studies showing mental rotation training transfer to different stimuli (Stransky, Wilcox, & Dubrowski, 2010; Wright et al., 2008), but it contrasts with other experimental work (Heil et al., 1998; Sims & Mayer, 2002; Tarr & Pinker, 1989). The discrepancies among these studies might come from the comparison of different kinds of training that include variations in terms of presentation mode and stimulus type, an idea in line with the present findings.

Moreover, the distinction between 2D and 3D tasks was confirmed, as well as its relevance to training paradigms. Training with 3D stimuli led to improvements in all tasks, whereas training with 2D stimuli impacted 2D assessments only. This finding is consistent with neuroimaging research showing distinct neural correlates for 2D and 3D mental rotation of spatial objects (Kawamichi et al., 2007) and corroborate previous work suggesting dimensionality crossing as a relevant factor mediating individual differences (Voyer et al., 1995). Training 2D mental rotation had a restricted effect on 2D transfer tasks whereas training mental rotation in 3D allowed tapping of general mental rotation processes. Therefore, 3D training led to improvements in 2D but also in 3D transfer tasks, via repeated dimensionality crossing.

The dissociation based on dimensionality was further established via correlation analyses. Tasks using different stimuli but sharing similar dimensional properties—such as 2D polygon and 2D body, or 3D polygon and 3D body—showed strong correlations, whereas tasks consisting of identical stimuli but of different dimensional properties did not. These results were consistent before and after training, for all tasks considered. Although it does not demonstrate a complete distinction between 2D and 3D mental rotation, this suggests core differences between processes involved in mental rotation within different dimensions. Conversely, it suggests similar components associated with mental rotation of various stimulus types.

The comparison of increases in videogame scores and mental rotation assessments provided additional insight into the mechanisms underlying improvements. Specifically, Tetris improvements were exclusively correlated to gains in 2D tasks, whereas Blockout improvements were correlated to gains in both 2D and 3D mental rotation tasks. This indicates that mental rotation improvements depend directly on training type, with 3D videogame training allowing wider changes, and that the magnitude of improvements in mental rotation follows score gains in videogame training.

Beyond the apparent distinction based on dimensionality, this study also refines our understanding of gender differences in mental rotation. As highlighted in the previous section, men and women playing Tetris showed comparable videogame performance throughout training, but gender differences were observed at every test session of Blockout training. This distinction was confirmed by pretraining assessments, showing a difference between men and women in 3D but not in 2D mental rotation performance. Altogether, these findings confirm that the well-documented gender difference in mental rotation is restricted to 3D processing, in line with previous literature (Neubauer, Bergner, & Schatz, 2010; Roberts & Bell, 2003).

The fundamental finding of the present study, the three-way interaction among training, gender, and time, shows that gender differences in 3D mental rotation tasks vanished after Blockout training, regardless of the particular type of stimuli used in the assessment task (polygon or body). This finding is consistent with work by Spence and colleagues who showed that women matched men on a spatial selective attention task after training on a first-person shooting videogame for as little as 10 hours (Spence, Yu, Feng, & Marshman, 2009), emphasizing the efficacy of this genre to spatial skills development. The present study is an additional step in this direction, showing that block videogame training can erase gender differences in the particular subcomponent of spatial ability that has yielded the largest and most reliable gender differences in favour of men: mental rotation. As such, this study underlines the malleability of gender differences in mental rotation and the possibility for any individual to improve over a short period of time given adequate training. This idea is encouraging, considering the number of activities that depend on high spatial ability (see, for a review, Hegarty & Waller, 2005).

In contrast with extensive transfer to all mental rotation tasks following Blockout training, gender differences in 3D mental rotation remained after training with Tetris. This indicates that, unlike dimensionality crossing, rotation itself is not what contributes to large gender effects in this kind of tasks. Consistent with this idea, Neubauer and colleagues showed that men outperformed women in 3D mental rotation when figures were presented in 2D format, but gender differences disappeared when the same figures were presented using virtual reality (Neubauer et al., 2010). They concluded that virtual reality presentation suppressed the need for dimensionality crossing, as perspective was rendered via enhanced depictions. Based on the present findings, it can be argued that Blockout training allowed women to overcome their difficulty in handling 2D presentation of 3D objects, by active exploration and manipulation of 3D features. This interactive process might have ultimately led to associations of particular depictions with corresponding overall structures, resulting in a quasi-effortless extraction of 3D properties presented two-dimensionally.

Despite the suppression of gender differences in 3D mental rotation assessments with Blockout training, however, men outperformed women in Blockout throughout the entire training phase. This might indicate positive impact of prior videogame experience or computer exposure in favour of men, a factor that was not assessed directly in the questionnaire that participants took prior to the study (the exclusion criterion was "extensive videogame experience") and that has proven relevant in a previous study (Quaiser-Pohl, Geiser, & Lehmann, 2006). Prior experience could be important considering the set of keys required to master the game (directional arrows, space bar, back and forth rotations on the x, y, and z axes). However, it is of relevance that computer experience did not seem to affect the Tetris group, possibly due to a less complicated set of keys required to play (directional arrows, space bar, back and forth rotations) and to a reduced cognitive load required to manipulate 2D blocks.

Directly related to cognitive load, another factor that may have heightened the effect described above is the inherent complexity of Blockout compared with all assessment tasks. As such, Blockout might be less prone to ceiling effects than the assessment tasks, a factor that could have restricted variance in performance among men and women. In that case, prior computer experience may have accentuated the effect, adding to the absence of ceiling effect to reach significance. Further research should determine whether the hypothesis of a more extensive computer experience is consistent, or whether other factors, such as videogame design (vs. assessment design), may have caused men's videogame scores to remain higher.

Despite clear findings, the present experiment also includes some limitations that need to be acknowledged. In particular, the number of participants for a behavioural study was low, especially to conduct correlation analyses. Stemming from this point, the absence of a control group does not allow strong inferences concerning the source of mental rotation improvements—that is, whether training is responsible for performance increases or whether these can be attributed to multiple-assessment effects. Related to this problem, the explicit emphasis on the cognitive benefits of training may have had implications difficult to gauge in the present study. This was used as a recruitment strategy, to motivate sustained commitment throughout training. Although not ideal, alternative incentives such as monetary reward could be equally questionable in a training study designed to have ecological implications. Outside the laboratory, improving cognitive abilities via an approach based on people's intrinsic motivation, rather than on more artificial incentives, appears to be a valid idea. A last limitation concerns the lack of data regarding the persistence of mental rotation improvements, a phenomenon demonstrated in previous work (Terlecki et al., 2008). It would be interesting to know whether the improvements observed could remain after training and, if so, for how long. This should be addressed in future experiments.

Despite these limitations, this study presents unambiguous evidence for a distinction between 2D and 3D mental rotation training effects, thus emphasizing the need to consider dimensionality as a critical factor in transfer. Altogether, the findings also offer promising perspectives for behavioural interventions designed to reduce differences in mental rotation, a critical ability to succeed in modern societies.

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