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HOW DOES HANDWRITING OF LETTERS AFFECT MIRROR-IMAGE DISCRIMINATION?

Maria Luísa da Silva Corbal

MESTRADO EM CIÊNCIA COGNITIVA

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Dissertação orientada pela Professora Doutora Tânia Fernandes e co-orientada pelo Professor Doutor Luís Correia

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To Artur and Filipa

Abstract

We explored whether training motor actions that match letter motor representations, supposedly supported by the dorsal visual stream, would contribute to mirror-image discrimination in tasks supported by the ventral visual stream, especially of letters for which orientation is the only feature that can assist discrimination, i.e., reversible letters.

Two groups of preliterate children trained motor actions during 20, 20-min daily sessions, in tablet games developed specifically for this study following human-computer interaction principles. Six children played the draw game, tracing and copying letters, and five children played the contact game (the control game) by moving the letters from an initial to a target point. Two reversible letters (d; p), two non-reversible (e; k), and two symmetrical letters (o; x) were used in both games. To evaluate the impact of motor training on orientation processing, children performed independent tasks before and after the training: a four-alternative forced-choice task with letters, and same-different matching tasks with letters and geometric shapes.

Children's performance in the games suggests that letter motor representations have emerged but only when the trained motor actions matched the letter shape (i.e., in the draw game) and they were more important for reversible than for non-reversible or symmetrical letters. The difficulty in mirror-image discrimination found in the four-alternative forced-choice task provide an original contribution showing that this difficulty is not specifically due to the working memory demands of the tasks in which it occurs. The results in the same-different tasks suggest that children became more sensitive to plane-rotation contrasts because in both games they had contact with letters differing by that contrast (i.e., d-p). Finally, when we compared both groups' performance in the independent tasks before and after the training, no significant differences were found. Therefore we could not confirm, or refute, the importance of training motor actions that match letter motor representations on mirror-image discrimination.

Keywords: letters; mirror-image discrimination; motor representations; motor training; ventral and dorsal visual streams; tablet games; human-computer interaction

Resumo

Investigámos se o treino de acções motoras correspondentes à representação motora de letras, supostamente suportado pela via visual dorsal, contribui para a discriminação de imagens em espelho em tarefas suportadas pela via visual ventral, em particular de letras cuja orientação é a única característica que permite a sua discriminação, i.e., letras reversíveis.

Dois grupos de crianças pré-letradas treinaram acções motoras com letras durante 20 sessões diárias de 20 min cada, em jogos de tablete desenvolvidos especificamente para este estudo segundo princípios da interacção humano-computador. Seis crianças treinaram no jogo draw, traçando e copiando as letras, e cinco crianças no jogo contact (jogo de controle) movimentado as letras de um ponto para outro. Utilizaram-se duas letras reversíveis (d; p), duas não-reversíveis (e; k) e duas simétricas (o; x). Para avaliar o impacto do treino no processamento da orientação, as crianças realizaram, antes e depois do treino, tarefas independentes dos jogos: uma tarefa de escolha forçada com letras, e tarefas de julgamento igual-diferente com letras e figuras geométricas.

A evolução do desempenho das crianças no treino sugere que só o treino de acções motoras correspondentes à forma da letra, no jogo draw, conduziu à emergência de representações motoras das letras, que foram mais importantes para o desempenho com letras reversíveis do que com letras não-reversíveis e simétricas. Os resultados na tarefa de escolha forçada deram um contributo original para o estudo da discriminação de imagens em espelho, ao mostrar que esta dificuldade não é devida em particular às exigências de memória de trabalho da tarefa em que ocorre. Os resultados nas tarefas igual-diferente sugerem que as crianças após o treino aumentaram a sensibilidade aos contrastes de orientação rotação-plana devido ao contacto nos dois jogos com esse contraste (i.e., contacto com as letras d e p). Finalmente, a comparação do desempenho dos dois grupos nas tarefas independentes antes e após o treino, não revelou diferenças significativas. Não foi assim possível confirmar, ou rejeitar, a importância do treino motor que corresponde à representação motora das letras na discriminação imagens em espelho.

Palavras-chave: letras; discriminação de imagens em espelho; representações motoras; treino motor; via ventral e via dorsal de processamento visual; jogos em tablete; interacção humano-computador.

Resumo Alargado

A aprendizagem da leitura e da escrita provoca importantes alterações nas estruturas cerebrais. Uma evidência de tal impacto é a existência de uma área no giro fusiforme esquerdo do cortex occipito-temporal que em letrados é mais activada durante a percepção visual de palavras ou de pseudo-palavras (no sistema de escrita em que os participantes aprenderam a ler e a escrever), do que perante outros estímulos visuais (McCandliss, Cohen & Dehaene, 2003). Esta área, denominada área da forma visual das palavras (VWFA, do inglês Visual Word Form Area; McCandliss et al.), é sistematicamente identificada em letrados, independentemente da idade em que aprenderam a ler e a escrever (Dehaene, Pegado et al., 2010) e do sistema de escrita em que o fizeram (Dehaene, Nakamura et al., 2010).

Dado que a invenção da escrita é recente (aproximadamente 5000 anos) no panorama da evolução humana, Dehaene e Cohen (2007, 2011; Dehaene, 2009) propõem que a especialização da VWFA não será consequência de pressões evolucionárias, mas sim da reciclagem de uma região com funções próximas das necessárias a esta invenção cultural. De facto, a região ventral occipito-temporal onde se localiza a VWFA, é parte da via visual ventral que suporta o reconhecimento visual de objectos, e por isso tem já propriedades adequadas ao reconhecimento visual de palavras (ver Hoffman & Logothetis, 2009). A reciclagem terá de ocorrer porque uma das suas propriedades originais dificulta a aprendizagem da leitura e da escrita em sistemas de escrita com caracteres em espelho, i.e., caracteres que são reflexões laterais resultantes de uma rotação de 180º em torno do eixo vertical (ou seja, durante a rotação a imagem sai fora do plano; e.g., no alfabeto latino, b-d, p-q): é a propriedade de *invariância em espelho*, em consequência da qual imagens em espelho são reconhecidas como o mesmo percepto. De notar que estudos electrofisiológicos mostram que neurónios da zona infero-temporal de primatas não-humanos (homóloga da região occipito-temporal em humanos) processam imagens em espelho como o mesmo percepto, mas não imagens rodadas no plano segundo o mesmo ângulo de 180º (e.g., ⌠-⌡; Logothetis, Pauls, & Poggio, 1995; Rollenhagen & Olson, 2000).

Tal como a investigação tem mostrado, bebés (Bornstein, Gross, & Wolf, 1978), crianças pré-letradas (Fernandes, Coelho, Lima & Castro 2017; Fernandes, Leite, & Kolinsky, 2016) e adultos iletrados (Fernandes et al., 2016, 2017; Fernandes & Kolinsky, 2013; Kolinsky et al., 2011), apresentam dificuldade na discriminação de imagens em espelho. Também adultos letrados em sistemas de escrita sem caracteres em espelho (e.g., Tamil) têm dificuldade nessa discriminação (Danziger & Pederson, 1998). A condição obrigatória para inibir a propriedade de invariância em espelho da via visual ventral é a aquisição de literacia (i.e., aprender a ler e a escrever) num sistema de escrita com caracteres em espelho. Uma vez desenvolvida, a capacidade de discriminação de imagens em espelho torna-se automática durante o reconhecimento visual, o que se traduz no processamento da orientação mesmo quando é prejudicial para a tarefa (Kolinsky & Fernandes, 2014; Pegado, Nakamura, Braga et al., 2014; Fernandes et al., 2016).

Para identificar quais os mecanismos que durante a aprendizagem da leitura e da escrita podem contribuir para o desencadear da capacidade de discriminação de imagens em espelho é importante ter presente que os estímulos visuais são processados em simultâneo pela via visual ventral e pela via visual dorsal que têm objectivos e propriedades distintas (e.g., Valyear, Culham, Sharif, Westwood, & Goodale, 2006). Enquanto a via ventral, ou via da *visão-para-percepção*, está dedicada ao processamento da informação para efeitos de reconhecimento, a via dorsal processa a informação visual com o objectivo de planear e conduzir as acções motoras a realizar sobre os objectos, ou seja, é a via da *visão-para-acção* (Goodale & Milner, 1992; Milner & Goodale, 2008). Ao contrário do que acontece com a via ventral, a via visual dorsal é sensível à diferença entre imagens em espelho, i.e., à orientação (Valyear et al., 2006), tendo sido identificada uma área nesta via que é sensível às diferenças de imagens em espelho de objectos manipuláveis (Rice, Valyear, Goodale, Milner, & Culhamb, 2007). Estes, são objectos que apresentam uma forte relação entre a sua forma e a acção motora adequada ao seu manuseamento (e.g., pegar numa faca pelo cabo); a sua visualização passiva, ao contrário do que acontece com objectos que não apresentam uma relação sensoriomotora forte (i.e., objectos não-manipuláveis; e.g., relógio), activa automaticamente o programa motor necessário ao seu manuseamento (Murata et al., 1998).

Tendo isto presente, Fernandes e colegas analisaram o desempenho de adultos (Fernandes & Kolinsky, 2013; Fernandes et al., 2017) e crianças (Fernandes et al., 2017) na discriminação de imagens em espelho de objectos manipuláveis e não manipuláveis, e propuseram que a discriminação de imagens em espelho em tarefas de visão-para-percepção poderá beneficiar da co-activação de processos visuomotores suportados pela via visual dorsal, uma vez que parece que só a informação motora associada aos estímulos a discriminar poderá apoiar não-letrados na discriminação de imagens em espelho.

À semelhança do que se passa com objectos manipuláveis (ver Grèzes & Deceti, 2000), a visualização de letras activa não só áreas visuais mas também motoras, possivelmente porque a experiência com letras não é apenas visual, mas também motora, através da escrita (James & Gauthier; 2006). Tal como estudos com adultos letrados e crianças pré-letradas têm mostrado, o treino de caracteres através de escrita manual conduz a um melhor desempenho na discriminação de imagens em espelho desses caracteres, do que treino em computador ou treino apenas visual (James, 2010; Longcamp et al., 2008; Longcamp, Zerbato-Poudou, & Velay, 2005).

Com base na literatura revista formulámos então a hipótese em que assenta o presente trabalho: se a discriminação de imagens em espelho pode ser facilitada pela operação da via visual dorsal então, realizar treino motor na representação sensoriomotora das letras, i.e., traçando letras, que supostamente será suportado pela via visual dorsal, deverá contribuir para o correcto processamento da orientação das letras. Este impacto deverá ser mais importante para letras cuja orientação é a única característica que permite a sua discriminação, i.e., letras reversíveis (no alfabeto latino as letras b, d, p, q), do que para letras que podem ser discriminadas pela forma uma vez que os seus contrastes de orientação não correspondem a letras do alfabeto, i.e., letras não-reversíveis.

Para testar esta hipótese desenhámos um estudo longitudinal no qual 11 crianças pré-letradas, em dois grupos, efectuaram treino motor com letras, em jogos desenvolvidos especificamente para este projecto segundo os princípios de interacção humano-computador das Ciências Computacionais (cf. Nielsen, 1993). Cada grupo jogou um de dois jogos: o jogo draw, no qual seis crianças efectuaram treino motor traçando e copiando letras; ou o jogo de controle, o jogo contact, no qual cinco crianças movimentaram letras de um ponto para outro, através de percursos pré-definidos ou livremente. Em ambos os jogos, e na mesma sequência pré-definida, foram apresentadas as mesmas seis letras: duas letras simétricas (o; x, e quatro letras assimétricas, duas reversíveis (d; p) e duas não reversíveis (e; k). O treino foi realizado durante 20 dias, em duas sessões consecutivas diárias de 10 min cada. Em cada 10 sessões (cinco dias de treino) as crianças podiam completar com sucesso 10 tarefas (traçado/movimentação) com cada letra. Para realizarem as tarefas com sucesso as crianças não deveriam cometer erros, que eram controlados pelos jogos. O desempenho das crianças nos jogos foi analisado, considerando o número de tarefas realizadas com sucesso, o número de tentativas feitas para realizar com sucesso cada tarefa apresentada e o número de erros efectuados, em quatro períodos de treino (i.e., T1, T2, T3 e T4), cada um referente a 10 sessões de treino consecutivas.

Para verificar a transferência da aprendizagem no treino motor para tarefas independentes de visão-para-percepção, o que permitiria comprovar a nossa hipótese, as crianças realizaram em computador, antes e depois do treino, uma tarefa de escolha forçada entre quatro possibilidades, semelhante à utilizada em Li & James, 2016, e tarefas de julgamento igual-diferente, já utilizadas em estudos anteriores (e.g., Fernandes et al. 2016). Na tarefa de escolha forçada, avaliaram-se os efeitos do treino na aprendizagem das letras treinadas e na capacidade de discriminação de contrastes de orientação imagem em espelho e rotação plana de 180º. Em cada ensaio as crianças viam uma letra-alvo, seguida de uma matriz onde essa letra era apresentada entre três distractores: no caso de letras simétricas, duas outras letras, e um símbolo não-linguístico; no caso de letras assimétricas, uma outra letra, um símbolo não-linguístico e um contraste de orientação que podia ser uma imagem em espelho (distractor *imagem-espelho*) ou uma rotação plana (distractor *rotação-plana*) da letra-alvo. As crianças deveriam apontar a letra-alvo nessa matriz. Foi medida precisão nas respostas.

As tarefas de julgamento igual-diferente foram realizadas com letras e figuras geométricas apresentadas em três orientações: normal, imagem em espelho e rotação plana de 180º. Em cada ensaio apresentaram-se dois estímulos sequenciais que podiam ser iguais (ensaio *idêntico*), imagens em espelho (ensaio *imagem-espelho*), rotações planas de 180º (ensaio *rotação-plana*) ou diferentes (forma e orientação diferentes; ensaio *diferente*). As crianças tinham de decidir se o segundo estímulo era igual ao primeiro. Para cada material, foram realizadas duas tarefas que diferiram no critério de julgamento: numa, para avaliar o processamento automático da orientação, a decisão era baseada na forma dos estímulos apresentados (i.e., as crianças deveriam responder igual em ensaios idêntico, imagem-espelho e rotação-plana); na outra, para avaliar o processamento explícito da orientação, a decisão deveria ser efectuada com base na orientação dos estímulos (i.e., as crianças deveriam responder igual apenas em ensaios idêntico). Mediram-se a precisão e os tempos de reposta.

Os resultados obtidos nos jogos sugerem a emergência de representações motoras das letras treinadas, como consequência do envolvimento da via visual dorsal em acções motoras que correspondem à forma das letras, uma vez que as crianças que treinaram no jogo draw melhoraram significativamente o seu desempenho de T1 para T4 com os três tipos de letras, mas não as que jogaram o jogo de controle. Também, tal como tínhamos preconizado, os resultados no jogo draw evidenciaram que a activação da representação motora das letras foi mais importante para letras cuja orientação é característica diagnóstica, i.e., letras reversíveis, do que para letras cuja discriminação não tem que assentar no processamento da sua orientação, i.e., letras não-reversíveis e simétricas (Pegado, Nakamura & Hannagan, 2014; Treiman & Kessler, 2011).

Os resultados na tarefa de escolha forçada mostraram que as crianças foram significativamente menos precisas nos ensaios com distractor imagem-espelho do que com distractor rotação-plana, em conformidade com resultados anteriores (Fernandes et al., 2016) e consistente com a proposta de que os contrastes de orientação imagem-espelho e rotação-plana poderão ser processados por mecanismos independentes (Turnbull & McCarthy, 1996). Mais ainda, estes resultados dão um contributo original ao mostrarem que a dificuldade que crianças pré-letradas têm na discriminação de imagens em espelho não é consequência particular das exigências de memória de trabalho das tarefas de julgamento igual-diferente habitualmente utilizadas (e.g., Casey, 1986; Gibson, Gibson, Pick & Osser, 1962; Fernandes et al., 2016; Kolinsky et al., 2011). Tanto quanto sabemos, esta dificuldade tinha sido demonstrada apenas em tarefas igual-diferente com julgamento baseado na orientação, que têm exigências de memória de trabalho, superiores às da tarefa de escolha forçada.

Após o treino, todas as crianças foram significativamente mais precisas nas tarefas igual-diferente do que antes do treino. Foram também significativamente mais rápidas com figuras geométricas e tenderam a ser mais rápidas com letras. É possível que tal se deva à experiência adquirida nos procedimentos de teste, durante a fase pré-treino, os quais exigiam que as crianças tivessem presente qual a tecla do computador que deviam premir consoante a resposta (igual ou diferente).

Nas tarefas igual-diferente em que o julgamento deveria ser baseado na forma dos estímulos, ou seja em que o processamento da orientação era prejudicial para o sucesso na tarefa, as crianças foram ainda mais lentas a responder nos ensaios rotação-plana do que nos ensaios idêntico, após o treino do que antes. Tal sugere que o treino nos dois jogos com as letras que diferem por uma rotação plana (i.e., p-d) contribuiu para aumentar a sensibilidade das crianças a este contraste de orientação. No entanto, com o presente desenho experimental, não é possível excluir a hipótese de que tal resultado se deva à experiência adquirida nos testes realizados antes do treino.

Não se encontrou diferença significativa no desempenho nas tarefas independentes do grupo que treinou no jogo draw e do grupo que treinou no jogo de controle, antes e após o treino. Dado que a não significância de resultados não permite a confirmação da hipótese nula (e.g., Dienes, 2011), não foi possível confirmar, ou rejeitar, a importância do treino de acções motoras que correspondem à representação motora das letras na discriminação de imagens em espelho. A reduzida dimensão da amostra terá contribuído para a não-significância da diferença entre os dois jogos (Bertamini & Munafò, 2012).

De referir que o presente trabalho permitiu mostrar que jogos desenvolvidos de acordo com os princípios de interacção humano-computador são uma ferramenta de treino eficaz em contextos de investigação com crianças pré-letradas, mantendo-as diariamente motivadas e comprometidas com programas de treino longos.

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1. Introduction

When writing was invented around the 4th millennium BC in Mesopotamia (Robinson, 2009), probably no one could have guessed the major changes this cultural invention would drive in the human society and could neither anticipate the impact it would have in the human brain and mind.

The impact of *literacy* (i.e., the ability to read and write) in the brain is demonstrated by the systematic finding of a functional region that is particularly sensitive to visual words. This area, called *Visual Word Form Area* (VWFA; McCandliss, Cohen & Dehaene, 2003), is located in the left fusiform gyrus, at the occipitotemporal cortex and shows greater activation when literate participants are presented with words and *pseudowords* (i.e., letter strings that obey to the phonological and orthographic rules of a language, and hence, can be read but have no meaning) written in a known script than with control stimuli (McCandliss et al., 2003). The VWFA is highly reproducible across people who are literate (Dehaene & Cohen, 2011), being located at the Talairach coordinates of x = -42, y = -52, z = -20, with a standard deviation of ~5 mm (McCandliss et al., 2003) independently of culture (e.g., in Japanese readers presented with kanji words and in French readers presented with alphabetic words: Dehaene, Nakamura et al., 2010) and of age at which literacy was acquired (i.e., in *unschooled ex-illiterate* adults, who did not go to school but learned to read during adulthood in alphabetization courses, and in *schooled literate* adults; Dehaene, Pegado et al., 2010).

This consistent finding seems to pose an evolutionary paradox (McCandliss, Cohen & Dehaene, 2003). There was not enough time so that such recent cultural activity (with ~5,000 years) could have imposed a selection pressure that would lead to develop such dedicated brain region (Dehaene, 2009). To shed light on this apparent paradox, Dehaene and Cohen (2007, 2011; Dehaene, 2009) proposed the *neuronal recycling hypothesis*, according to which a brain region with several original properties suited to process a cultural invention is reused and adapted to this new cultural purpose.

Indeed, the VWFA is an occipitotemporal region, part of the vis*ion-for-perception, ventral visual* stream (Goodale & Milner, 1992; Milner & Goodale, 2008) which, being devoted to object recognition, has several properties that are useful for reading. As Hoffman and Logothetis (2009) describe, this region shows size and position invariance (e.g., we perceive a, a, or a as the same letter). It responds to arbitrary associations, thus ignoring large feature differences between stimuli that we learned that belong to the same category (e.g., a, A, or *a* are the same letter), while being sensitive to minute but diagnostic features (e.g., the difference between E and F, a minor horizontal feature). This region is also sensitive to orientation variations in the image plane or *plane rotations* (e.g., of 90º, which allows us to easily discriminate Z and N). In fact, the most common configurations of line junctions found in the natural environment match those found in writing symbols of both ancient and current scripts (Changizi, Zhang, Ye & Shimojo, 2006). However, precisely because the occipitotemporal region did not evolve for supporting reading, according to the neuronal recycling hypothesis (Dehaene & Cohen, 2007, 2011; Dehaene, 2009) some of the original properties of this brain region may not be well suited to the novel cultural function. One such property is *mirror-image invariance*: neurons of the inferotemporal cortex of the macaque (homologue of the human occipitotemporal region) process mirror images (i.e., reflections related by a 180º rotation outside the image plane, e.g., b and d) as the same percept (Logothetis et al., 1995; Rollenhagen & Olson, 2000).

Mirror invariance is not a perceptual bias but rather an adaptive mode of processing, possibly selected throughout evolution (Gross & Bornstein, 1974). Usually, when mirror images occur in nature they correspond to profile views of the same entity. Therefore, being able to distinguish them would have no advantage for recognition (Gross & Bornstein, 1974).

Mirror invariance is a cross-species phenomenon found in octopuses, bees, or pigeons (e.g., Todrin & Blough, 1983). Interestingly, in non-human primates, inferotemporal neuron recording showed that mirror-image contrasts are hard to discriminate but this difficulty does not hold to other orientation contrasts including plane rotations with the same angular difference from the standard view (i.e., 180º; Logothetis et al., 1995; Rollenhagen & Olson, 2000).

In humans, mirror invariance is found throughout development. Four-month old infants fail to discriminate mirror images of oblique lines but are able to discriminate between two oblique lines that are not mirror images (Bornstein, Gross, & Wolf, 1978). *Preliterate* children (i.e., who did not yet learned to read and write) also show difficulty in discriminating mirror images (e.g., b – d), and this difficulty is much stronger than that for 180º plane rotations (e.g., d – p; Fernandes, Leite, & Kolinsky, 2016). This difficulty in mirror-image discrimination is not a matter of development. *Illiterate* adults (i.e., with no neurocognitive deficit that could have precluded literacy acquisition, but who did not go to school nor learned to read and write solely due to socioeconomic and cultural reasons) show the same specific difficulty in mirror-image discrimination but are quite able to discriminate plane rotations (of 90º or 180º: Fernandes & Kolinsky, 2013; Kolinsky et al., 2011).

When learning a script with mirror symbols, as b and d, and p and q in the Latin alphabet, in order to become a fluent reader one needs to be able to discriminate mirror images. Prior studies have already shown that readers of scripts with mirror symbols (e.g., Latin alphabet, for Portuguese and French readers; Kana for Japanese readers) are quite able to discriminate mirror images (probably for the reader of this thesis this seems intuitive!). Mirror discrimination also becomes possible, not only for the written script, but also for other visual categories, either familiar (e.g., pictures of tools; Dehaene, Nakamura, et al., 2010; Fernandes, Coelho, Lima & Castro, 2017) or novel (e.g., geometric or blob-like shapes;

Kolinsky et al., 2011; Fernandes et al., 2016; Fernandes & Kolinsky, 2013). Whereas literate people (either children or adults) in such scripts are able to discriminate mirror images, literate people in a script with no mirror symbols as the Tamil syllabary, have difficulty in mirror discrimination, as shown by Danziger & Pederson (1998). Also, for illiterate adults, and *preliterate* children mirror-image discrimination is extremely hard. This difficulty was initially reported on studies examining *explicit* orientation discrimination, i.e., when orientation is critical to discrimination, using *orientation-based* tasks as in same-different matching tasks where participants are asked to decide if two sequential stimuli have the same orientation or not, responding *same* only when the two stimuli are *identical* (exact matches, e.g., d – d; Casey, 1986; Gibson, Gibson, Pick & Osser, 1962; Fernandes et al., 2016; Fernandes & Kolinsky, 2013; Kolinsky et al., 2011). The stimuli in the *different*-response trials can be mirror images (e.g., d - b), plane rotations (e.g., d - p) or fully-different (when both shape and orientation differ; e.g., d - k). With this orientation-based task, Fernandes, Kolinsky and colleagues showed that the emergence of mirror-image discrimination does not depend on schooling or maturation given that illiterate adults (and adult readers of Tamil, Danziger & Pederson, 1998) show the same difficulty as preliterate children in mirror-image discrimination (Fernandes, Coelho, Lima & Castro 2017; Fernandes et al., 2016; Fernandes & Kolinsky, 2013; Kolinsky et al., 2011).

Mirror-image discrimination is thus triggered by learning a script with mirror symbols. Impressively, for readers, mirror-image discrimination even becomes automatic during visual recognition of non-linguistic objects in the sense that orientation is processed even when irrelevant to the current task. In studies that explored automatic processing of orientation in same-different matching tasks, participants were required to respond *same* when the two stimuli had the same shape regardless of orientation (i.e., for identical, mirror-image, or plane-rotation pairs), and to respond *different* only when the stimuli differed in shape (i.e., fully-different pairs, e.g., d - k), thus the matching criterion was based on shape. On this shape-based task, readers had worse performance on mirror-image trials than on identical trials, indicating sensitivity to mirror-image differences even when these were irrelevant to the task. No such *mirror cost* was found on non-readers (Kolinsky & Fernandes, 2014; Pegado, Nakamura, Braga et al., 2014; Fernandes et al., 2016). In fact, even beginning readers at the end of the 1st grade are already slower on mirror-image trials than younger preliterate children, showing that as soon as mirror-image discrimination is triggered by learning to read, it becomes automatized during visual object processing.

Mirror-images are not processed in the same way by the ventral and the *dorsal visual* streams. These two streams operate simultaneously during visual processing but for different purposes, even during passive viewing (e.g., Valyear, Culham, Sharif, Westwood, & Goodale, 2006). Whereas the ventral stream that projects from the primary visual cortex to the inferotemporal lobe is devoted to object identification, as aforementioned, the dorsal, *vision-for-action* stream projects to the posterior parietal lobe and is responsible for motor programming and movement control so one can interact with objects in the world (Goodale & Milner, 1992; Milner & Goodale, 2008). Furthermore, the two streams present different properties. Whereas ventral occipitotemporal regions (including the VWFA) show similar responses to mirror images of non-linguistic objects, dorsal stream regions as the lateral occipitoparietal junction (lOPJ) are sensitive to mirror-image differences.

In an fMRI study in which participants performed a priming semantic task where the prime could be identical or a mirror image of the target, and participants had to perform a size decision task on images of animals and familiar objects, repetition suppression (i.e., the neural correlate of behavioural priming) was found at the left fusiform gyrus in the ventral region (where the VWFA is located) for targets preceded by either its mirror image or its exact match (Dehaene, Nakamura, et al., 2010). A similar pattern of results was found at this ventral region in another fMRI study during passive viewing (Valyear et al., 2006). On its turn, the dorsal visual stream showed to be sensitive to lateral mirror images, as stronger activation was found in the lOPJ when mirror images of the objects were presented but not when objects were in the same orientation. In a following study, Rice, Valyear, Goodale, Milner, & Culhamb (2007) showed that this pattern of activation of the dorsal visual stream is especially observed for mirror images of *graspable* objects (i.e., objects for which visual configuration has a strong association with the motor grasping program; e.g., a knife, which is grasped by the handle so that one can cut a slice of bread). Indeed, graspable objects, in contrast to those without such strong visuomotor association, i.e., *non-graspable* objects (e.g., a watch), automatically invoke the specific motor program that must be used to perform the grasping action, even in passive viewing of pictures, as shown by activation in premotor regions in these conditions (Murata et al., 1998).

From this prior evidence, Fernandes and Kolinsky (2013; see also, Fernandes et al., 2017) have hypothesized that, on the one hand, during a perceptual task (i.e., orientation-based same-different task), presumably supported by the ventral stream, mirror-image discrimination would be especially hard for illiterate adults but not for ex-illiterate or literate adults. On the other hand, during a visuomotor task (i.e., virtual grasping), presumably supported by the dorsal stream, there would be no impact of literacy on mirror-image discrimination. To test this hypothesis these authors used a sequential virtual grasping task. Participants were asked to decide for each stimulus (a picture of a familiar graspable object) which hand they would use to grasp it without changing their position relative to the object. Unbeknownst to participants, in the critical trials sequential stimuli could be either identical, mirror images or different objects. Supporting their hypothesis, in the vision-for-perception task Fernandes and Kolinsky added to prior findings by showing that illiterate adults had more difficulties in mirror-image discrimination than ex-illiterate and literate adults, not only of unfamiliar, geometric-like shapes, but also of pictures of familiar objects. Interestingly, the difference between groups was specific to mirror images, as illiterate adults were as able as the other groups to discriminate 180º plane rotations, in line with the properties of mirror invariance and plane-rotation sensitivity of the occipitotemporal cortex (Hoffman & Logothetis, 2009; Logothetis, et al, 1995; Rollenhagen & Olson, 2000). On the other hand, in the visuomotor task, illiterate adults were as able as literate to discriminate mirror images. Therefore, the impact of learning a script with mirror-image symbols is specific to vision-for-perception processes. When orientation processing relied on visuomotor information, illiterate adults did not show any difficulty in mirror-image processing. Such finding led these authors to suggest that mirror-image discrimination during vision-for-perception could benefit from the co-activation of visuomotor processes supported by the dorsal visual pathway.

Supporting this hypothesis, in a following study, Fernandes et al. (2017) used a visual search task on which the target differed from the distractors only in orientation; all stimuli in the visual array had the same identity. Illiterate, ex-illiterate, and literate adults, and preliterate children and beginning readers were asked to locate the target, either a graspable or a non-graspable object, among the orientation-contrast distractors. For both illiterate adults and preliterate children, mirror-image errors (i.e., selecting the mirror distractor as being the target) were the most frequent, but graspability did assist mirror-image discrimination. Both groups of non-readers presented fewer mirror-image errors for graspable than non-graspable objects. Interestingly, the advantage of the activation of motor information only affected their performance for mirror-image contrasts, not for plane rotations. In contrast, for readers, lateral mirror-image errors were much reduced and were not strongly affected by motor information. Whereas for readers literacy seems the responsible factor for overcoming mirror invariance, for non-readers graspability seems to be the only mechanism available to assist mirror-image discrimination.

As with the representation of graspable objects, which have well-defined visuomotor programs, letters also have perceptual and visuomotor representations. Note that the perception of graspable objects lead to activation of both motor and visual brain regions (Grèzes & Deceti, 2000). Probably because we interact with letters by reading and by writing, letter recognition is also supported by a neural network that includes motor and visual processing regions (James & Gauthier, 2006). In fact, when adult readers are presented with visual words during a recognition task, the *Exner area*, a left premotor region thought to contain the motor programs necessary to produce handwriting gestures, is activated (Longcamp, Anton, Ross, & Velay, 2003). The specific motor program associated with each letter is thus automatically invoked when letters are perceived (Nakamura et al., 2012). Therefore, the motor experience gained during handwriting could assist mirror-image discrimination of letters, because then letters would also become graspable objects.

One of the reasons for the importance of handwriting would thus lie on training the specific visuomotor representations of letters. Prior behavioural studies have already shown that handwriting assists mirror-image discrimination of symbols of a script. Longcamp et al. (2008) trained adults on symbols of an artificial script (adapted from Bengali and Guarajati alphabets) by handwriting and by typing during three weeks in 1-hour session per week. These readers showed better explicit mirror-image discrimination for symbols learned by handwriting than by typing. Similar results were found with preliterate children who trained upper-case letters for three weeks in one 30-min session per week (Longcamp, Zerbato-Poudou, & Velay, 2005), or upper- and lower-case letters and words once a week for four weeks (James, 2010). In two other studies, the pattern of results also suggests that mirror-image discrimination was facilitated by handwriting training: in a four-alternative forced-choice task, children had to recognize the trained symbols among three distractors, i.e., a mirror image of the trained letter, and two transformations of the trained letter (i.e., without one stroke, and with an additional stroke; Longcamp et al., 2005), or a mirror image of the trained letter, another letter, and its mirror image (James, 2010). Children who had trained by handwriting were more successful in recognizing the trained letters than those who trained by typing (Longcamp et al., 2005) or by mere visual exposition (James, 2010).

Based on the reviewed literature, we thus hypothesized that if mirror-image discrimination during visual object recognition could be assisted by the operation of the dorsal stream, then training on the specific visuomotor representations of letters (supported by the operation of the dorsal stream) would impact on letter orientation processing during recognition. Such handwriting training would be more important for discrimination of *reversible* letters (which differ solely by orientation contrast; e.g., n - u) than for *non-reversible* letters (for which an orientation transformation does not correspond to a different letter of the script; e.g., R - Я). Given that reversible letters that are plane rotations (e.g., d - p) are already well discriminated before learning the Latin alphabet (e.g., Bornstein et al., 1978; Fernandes et al., 2016, 2017), the impact of handwriting training would be particularly strong for mirror-image letters (e.g., d and b; Fernandes et al., 2016).

To test this original hypothesis which to the best of our knowledge remains hitherto untested, we designed the present longitudinal training study. Two groups of preliterate children were exposed to the visual form of six letters in one of two tablet games during 20 sessions of 20-min each. Both games involved motor training on the letters. In the critical, *draw* game children trained letter handwriting by tracing and copying the letters. In the control, *contact* game, children moved the letters along defined paths and freely, and hence, did not train on the specific motor representations of letters but had the same amount of visual and motor experience with letters as children in the draw game. To ensure that children on the control game would not associate specific motor actions to each letter, the path proposed for each letter differed within each session, as shown in Fig. 1. Copying tasks were included in the draw game based on Li and James (2016), to allow children to produce their own instances of the letters. According to James and Engelhardt (2012), copying seems to be the only handwriting practice that allows the visuomotor brain network supporting reading to be recruited during visual perception of the copied letters. The contact game included a task in which children moved the letters freely (i.e., no path was presented), to ensure matching of both games (as copying is a free-movement task as well) as much as possible. The six letters used in the games were two symmetrical letters (i.e., x and o) and four asymmetrical letters: two reversible (i.e., d and p), and two non-reversible (i.e., e and k). Two symmetrical letters were used given that based on the properties of the visual system, the common characters of different written scripts, and prior behavioural results with children of this age, we know that these letters are easily recognized and highly familiar to preliterate children (Changizi & Shimojo, 2005; Treiman & Kessler, 2011; Wagemans, 1997). The two reversible letters were selected because their mirror images are real letters that were not in the game (b; p) and they present different frequency-arrangement in the Latin alphabet: d presents a less common arrangement (coda to the left of the hasta) than p (coda to the right of the hasta; e.g., Treiman & Kessler, 2011). Therefore we used a very stringent test of our hypotheses because if the game had any impact on mirror-image discrimination it would not be due to explicit training of this orientation contrast in the draw game. The two non-reversible letters were selected so that we could compare the results for reversible letters and for non-reversible ones with similar visual complexity. By using these three types of letters we thus examined whether handwriting was especially important for recognition of reversible letters.

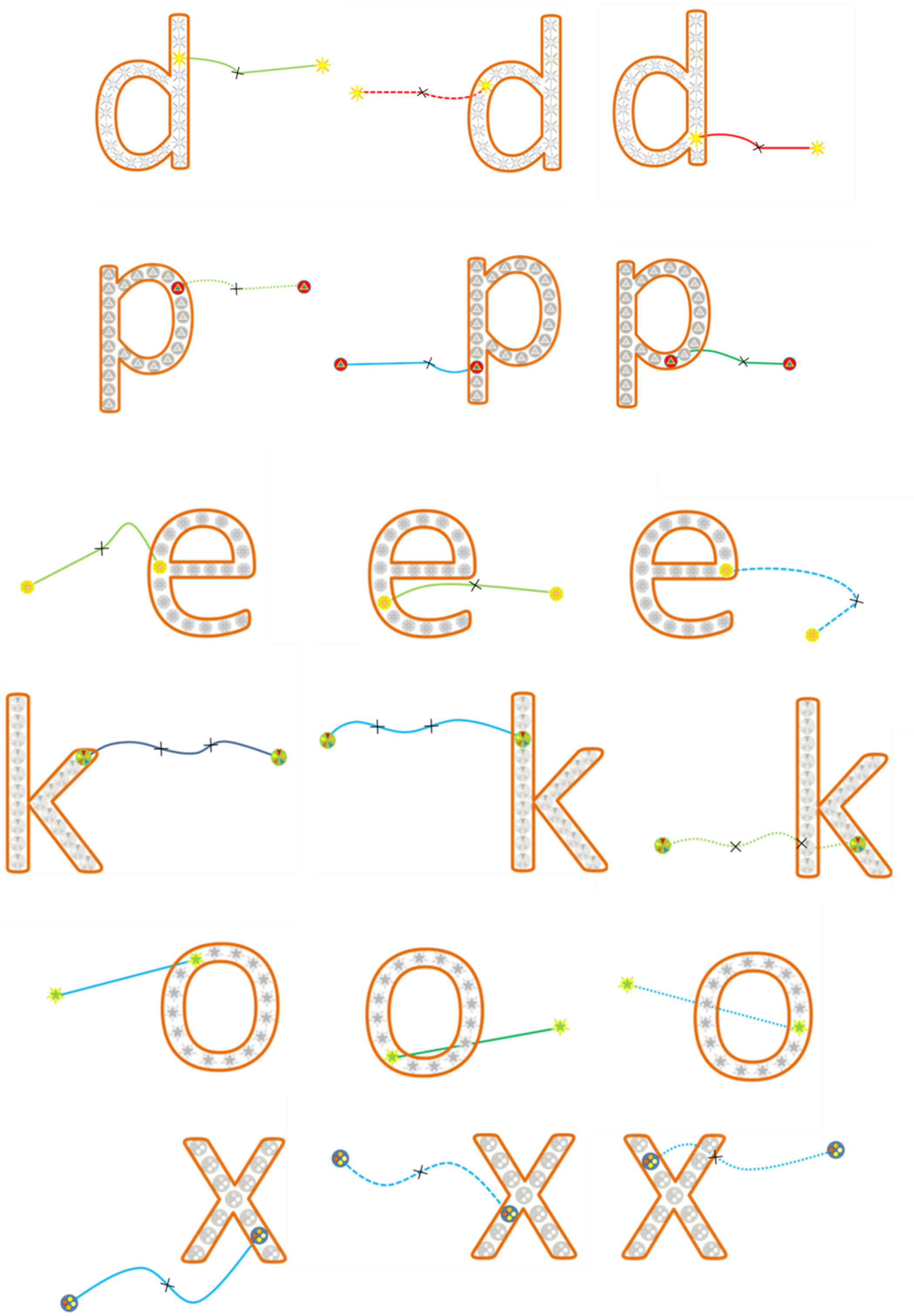

Figure 1 Moving paths in the contact game.

Each letter was moved along three different paths. The number of segments of each path matches the number of strokes of the correspondent letter (reversible letters: d and p, two strokes; non-reversible letters: e, two strokes, and k, three strokes; symmetrical letters: o, one stroke, and k, three strokes). The symbol × denotes the limits of the segments on each path with more than one segment.

The games were designed and built as part of this thesis. To ensure that children would be engaged in training and would learn the intended motor actions, the games were designed to be playful and to have adequate levels of difficulty (i.e., challenges and goals matched with the children's skills), while providing regular feedback to children (Kiili, 2005; Martinovic, Burgess, Pomerleau, & Marin, 2016; Ryan & Deci, 2000). We adopted a human-centred approach to the development of the games, from Computer Science. Games were thus designed considering *utility*, which is related with the ability that a system has to allow the user to do what is needed, and *usability,* which is concerned with the way users interact with the system (Nielsen, 1993). The games allowed children to perform the desired motor actions, preventing them to persist on incorrect movements. To this aim, the games controlled whether children started the movements at the right point and performed them in the right sequence. The game also complied with children's accuracy in movement execution given that human movements are variable affecting execution precision, even in well trained motor tasks (van Beers, Haggard, Wolpert, 2008), and especially at this age (e.g., Takahashi et al., 2003). To ensure that children would be focused on what was relevant for the task no elements besides the necessary ones were displayed in the task scenes. Furthermore, the games were intended to be easy to learn and to deliver a pleasant playing experience. As detailed in the Method (Chapter 2), the games presented demonstrations of how to successfully perform the tasks, and delivered feedback regarding children's performance: positive feedback intended to keep them motivated and engaged (Ryan & Deci, 2000); corrective feedback that allowed children to learn to avoid errors (Norman, 1983) and to adjust motor planning in order to increase movements precision (van Beers, 2009). The games included elements that children would hopefully find amusing (e.g., a clown, a princess, and a magician that children could choose from to become their assistant in the game). Tablets were chosen as interface because before children first contact with letters they already have experience with digital tools, e.g., tablets, which they enjoy and engage with (Livingstone, Marsh, Plowman, Ottovordemgentschenfelde, & Fletcher-Watson, 2014; Nacher, Jaen, Navarro, Catala, & González, 2015).

As a preview of the steps considered in the results (Chapter 4), to examine training efficacy, we first assessed whether learning had occurred during training with the tablet games and next we explored whether learning *transferred* to *independent* tasks, outside training. Learning in the games was assessed by exploring how children's performance evolved along training. We analysed the number of *tracing* tasks (in the draw game) and of *moving* tasks (in the contact game) successfully completed, the number of attempts made to complete these tasks, and the number of errors made in these attempts. We predicted that children trained in the draw game would improve more or faster (considering the number of sessions) along the game than children in the contact game. More specifically, for children in the draw game, the benefit would be especially on reversible letters than on non-reversible or symmetrical ones, whereas children in the contact game would not show such difference in performance between letter types.

Given the stronger complexity of the motor actions in the draw game (curvature of letter strokes and letters with more than one stroke) than in the contact game (Meulenbroek & Van Galen, 1986, 1990), it was also expected that children in the former game would complete fewer tasks than children in the latter game.

To assess *transfer effects* children were assessed in independent tasks both before and after the training, that is, in two testing phases. Tasks used letters, including those *trained* in the games and *untrained* letters, and geometric shapes with similar visual complexity as letters (both materials used in the study from Fernandes et al., 2016).

To minimise the impact of uncontrolled factors on children's performance after the training, the present study followed the best practices advocated by Simon et al. (2016) on their thorough literature review on longitudinal training studies claiming for transfer effects, namely: (i) the two groups of children played games in order to minimize the impact of motivational factors on performance after the training; (ii) children of both groups trained visuomotor skills and for the same amount of time; (iii) the two games differed only on the motor actions trained, albeit being matched in the number of motor components to be performed on each letter (Fig.1); (iv) children were tested before training and the two groups were matched on the pre-training results (see Chapter 3) so that any improvement to be found after training would not be due to significant differences between groups in pre-training performance; and (v) the groups were randomly assigned to one of two games, thus, uncontrolled factors were equally likely to impact any of the groups. Specific to the present study, we assessed children's letter knowledge to ensure that children did not know the mirror-letter pairs of the Latin alphabet (i.e., b-d and p-q) before the training. Children's letter knowledge was assessed again after training to control for its impact on mirror-image discrimination, given that preliterate children's sensitivity to mirror images differences is positively correlated with the number of letters they know (i.e., the better their letter knowledge, the more sensitive to mirror images differences; Fernandes et al., 2016).

Transfer effects were thus examined, first, in a four-alternative forced-choice task on letters (similar to that used by Li & James, 2016). Children were asked to decide which of four stimuli (including non-letter symbol and letters) corresponded to the specific letter previously presented, i.e., the target letter. For asymmetrical letters, the distractors included an *orientation* distractor, either a mirror image or a 180º plane rotation of the target letter, which allowed assessing whether mirror-image discrimination would be affected by training with the tablet games. We predicted that, regardless of testing phase, children would have better performance for symmetrical than asymmetrical letters, given the high sensitivity of the visual system to symmetry (Wagemans, 1997). Also, for the letters trained in the games children would have better performance on the post- training than on the pre-training phase, regardless of game, denoting an impact of training on letter recognition. We also expected that when the distractors included a mirror-image of the target letter, children would make more errors than when the orientation distractor was a 180º plane rotation (e.g., Bornstein et al., 1978; Casey, 1986; Fernandes et al., 2016, 2017). Importantly, if training the motor actions that match letter motor representations assisted mirror-image discrimination, which would then transfer to tasks that are independent from training, then children in the draw game would show a stronger decrease in errors on trials with mirror-image distractors relative to children in the contact game.

Next, we examined transfer effect in same-different matching tasks which differed on matching criterion: an orientation-based task to assess explicit orientation processing, and a shape-based task to assess automatic orientation discrimination. These tasks used four trial types as in previous studies (e.g., Fernandes et al., 2016): identical trials (e.g., d-d), mirror-image trials (e.g., d-b), plane-rotation trials (e.g., d-p), and fully-different trials (e.g., d-k). Moreover, two types of materials were tested: asymmetrical letters and geometric shapes. The letters were reversible and non-reversible given that prior studies suggested that mirror-image discrimination of letters might occur at different stages of processing depending on letter type (see Fernandes et al., 2016; Perea, Moret-Tatay, & Panadero, 2011). The asymmetrical geometric shapes were a novel material for all children that would inform about any spillover effect of training on other non-linguistic visual category (Fernandes et al., 2016).

In the orientation-based task children should respond *same* only on identical trials, and *different* on mirror-image, plane-rotation, or fully-different trials. Thus, if children in the draw game became sensitive to mirror-image differences due to tracing and copying along training, then they would show better performance on mirror-image trials after training, whereas children in the contact game would still show the same strong difficulty in mirror-image discrimination found at pre-training for both letters and geometric shapes (Casey, 1986; Gibson et al., 1962; Fernandes et al., 2016).

In the shape-based task, children should respond *same* on identical, mirror-image, and plane-rotation trials and *different* only on fully-different trials. If children in the draw game group became sensitive to mirror-image differences due to tracing and copying along training, then after training these children would show a stronger mirror cost for letters, indicating that they had become sensitive to mirror-image differences (Fernandes et al., 2016; Kolinsky & Fernandes, 2014; Pegado, Nakamura, Braga et al., 2014), whereas no such mirror cost was expected for children in the contact game.

2. Method

2.1. Participants

Seventeen 4- to 5-year-old children (10 girls, M_{age} = 58.70 months, *SD* = 4.31), who were Portuguese native speakers with no known history of mental or neurological disorder, were preliterate, and did not know all reversible letters of the Latin alphabet that are mirror images (i.e., d and b, p and q) assented to participate voluntarily after parents gave informed consent.

The study followed the Portuguese regulation for research in Psychology and was approved by the Deontological committee of Faculty of Psychology of Universidade de Lisboa.

Children participated in the pre-training phase after which three children were excluded due to their performance in the independent tasks (see below). As shown in Table 1, 14 children (M_{age} = 57.78 months, *SD* = 2.83) participated in the training phase, and were quasi-randomly assigned to the two groups (each trained in one tablet game) matched in age, gender, *p*s > .250, and pre-training results (see Chapter 3), so that we could ensure that any impact of training in post-training results was not due to differences between groups at pre-training. The two groups comprised seven children in the draw game group (3 girls) and seven children in the contact game group (5 girls).

Table 1 Mean and standard deviation for age and the ancillary measures - initial sample

	draw group (*N* = 7)		**contact group** (*N* =7)	
	M	***SD***	***M***	***SD***
Age (months)	57.83	2.97	57.72	2.93
Non-Verbal IQ (Raven)[a]	15.43	2.15	16.43	2.88
Visuospatial Working Memory (Corsi Block)[b]	6.00	1.83	6.00	2.31
Phonological Working Memory (MDS)[b]	6.57	1.51	7.14	1.57

Note: *M* - mean; *SD* - standard deviation. All $ts(12) < 1$, $ps > .450$. [a] Mean number of correct responses out of 36. [b] Mean number of correct trials in forward and backwards sequence.

Two children (one in the contact game, the other in the draw game) quitted during training and a third child did not complete the post-training phase. Thus, the final sample here examined included 11 children (7 girls, M_{age} = 58.17 months, *SD* = 2.96): six in the draw game (3 girls) and five in the contact game (4 girls). When we considered only the pre-training results of the children who went throughout all study phases, the two groups were still matched in age and gender (*p*s > .300), and in the pre-training results: ancillary measures (see Table 2), t-tests all *p*s > .085, and ANOVAs, all *p*s > .062 (see results in Chapter 3).

Table 2 Mean and standard deviation for age and the ancillary measures - final sample

	draw group (*N* = 6)		**contact group** (*N* = 5)	
	M	***SD***	***M***	***SD***
Age (months)	58.47	2.67	57.80	3.56
Non-Verbal IQ (Raven)[a]	15.17	2.23	16.40	3.36
Visuospatial Working Memory (Corsi Block)[b]	6.17	1.94	6.00	2.74
Phonological Working Memory (MDS)[b]	6.33	1.51	7.80	0.84

Note: [a] Mean number of correct responses out of 36. [b] Mean number of correct trials in forward and backwards sequence.

2.2. Materials and Procedure

This study followed a longitudinal training design of 12 weeks. In the pre-training phase children were tested individually in a quiet room at their school in four sessions (30-40 min session day); first, they were tested in the ancillary measures and only then in the independent tasks described below. At the end of this phase, children's results were examined in order to assign them to one of the two games so that the two groups were matched in pre-training performance (see Chapter 3). After the training phase with the tablet games, children performed all independent tasks again in a post-training phase comprising three sessions. All children received a sticker to motivate and reward them at each session, and in the last session they received a colouring or sticker book to thank them for participating in the study.

2.2.1. Ancillary measures

Children were tested in the ancillary measures only in the pre-training phase so that the two groups assigned to each of the two games were matched in general cognitive abilities known to be relevant to object orientation processing. These included three tests: a measure of nonverbal intelligence, i.e., the Coloured Progressive Matrices of Raven (Portuguese version: Simões, 2000), and two working memory tests, i.e., phonological working memory with the *Digit Span subtest* of Wechsler Intelligence Scale for Children (WISC III; Portuguese Version; Cegoc-TEA, 2003), and visuospatial working memory with the *Corsi block subtest* of Wechsler Memory Scale-III (WMS III; Wechsler, 1997).

2.2.2. Independent tasks

Five independent tasks were used as measures of training effectiveness on letter knowledge and on orientation processing (including on mirror-image discrimination), and hence, these tasks were applied in both pre- and post-training phases.

2.2.2.1. Letter knowledge tasks

Children were assessed in letter knowledge in the pre-training phase in order to identify if any child was already able to discriminate the two letter members of the mirror pairs of the Latin alphabet, in which case they would be excluded (none of the children were excluded). They were assessed again in the post-training phase given that mirror-image discrimination abilities are correlated with the number of letters that pre-literate children know (Fernandes et al., 2016).

Knowledge of upper- and lower-case letters was assessed in a *naming* task and in a *recognition* task (fixed order). Twenty-six letters (Arial font, size: 20) printed in two A4 pages (13 letters per page) in a random order were used in each case and task. Children were first presented with the upper-case and next with the lower-case letters. In the naming task, the experimenter pointed each letter and the child was asked to name it. In the recognition task, the experimenter named one letter (the two A4 pages were on the table in front of the child) and the child was asked to find the letter and point it out. Each correct response received one point (maximum score per letter-case and task: 26).

2.2.2.2. Four-alternative forced-choice task

To examine the learning of the six letters presented throughout training with the tablet games, and the impact of training on orientation processing, children were also assessed pre- and post-training in a computerized four-alternative forced choice task (henceforth, *4AFC;* for a similar task, see Li & James, 2016) using the six letters in the games (the trained set), and six other letters with similar visual and linguistic properties (the untrained set; see Table 3). Based on the pre-training results, one child was excluded due to 100% correct performance in this task on the trained set of letters.

In each trial, children first saw a fixation cross in the centre of the screen for 500 ms, after which they were presented with a target-stimulus for 1 s (screen resolution: 1366 x 768 pixels; refresh rate: 60 Hz). They were asked to look carefully to the target so that they next decided which of the four stimuli (presented in a 2 x 2 matrix) corresponded to the target. Children responded by pointing and the experimenter collected children's response using the numerical keyboard. After children responded or after 15 s if no response was provided, another trial begun. Stimuli presentation and data collection was controlled by E-Prime SP1 (https://www.pstnet.com/eprime). Children performed four blocks of 12 trials (order randomized) with a brief pause between blocks (24 trials with trained and 24 with untrained letters; the target occurred in each of the four locations of the matrix with equal probability).

As shown in Table 3, the target was presented with three distractors in the 2 x 2 matrix: for asymmetrical letters (reversible and non-reversible), the orientation distractor (a mirror-image or a 180º plane-rotation transformation), another asymmetrical letter, and a non-letter symbol; for symmetrical letters, two other letters and one non-letter symbol.

Before the experimental trials, children were presented with four demonstration trials, using non-letter symbols as targets. Children were warned that the target could appear in any of the four locations. To ensure that children understood the task, before the experimental trials they performed four practice trials with the non-letter symbols used in the demonstration trials.

Table 3 Target letters and distractors in the 4AFC task by letter set and letter type.

Letter set	Target letters	Letter type	Distractors			
			Symbol	Letter(s)	Orientation distractor	
					Mirror-image	Plane-rotation
Trained	e	Non-reversible	♉	q	ɘ	ə
	k	Non-reversible	♊	h	ꓘ	ʞ
	d	Reversible	↙	v	b	p
	p	Reversible	♌	a	q	d
	o	Symmetrical	✡	i/a	—	—
	x	Symmetrical	✧	b/k	—	—
Untrained	a	Non-reversible	♊	q	ɒ	ɐ
	h	Non-reversible	↙	b	ᖹ	ɥ
	b	Reversible	♉	i	d	q
	q	Reversible	✧	h	p	b
	i	Symmetrical	✡	v/h	—	—
	v	Symmetrical	♌	a/b	—	—

2.2.2.3. Same-different matching tasks

In order to directly examine the impact of letter training (throughout the tablet games) on orientation processing, children performed the two same-different matching tasks adopted in prior studies (cf. Fernandes et al., 2016) pre- and post- training. Based on the pre-training results, two children were excluded due to poor overall performance (below 50% correct).

The two tasks used the same material, trial-type and procedure. In each trial, participants were presented with two sequential stimuli separated by a mask in order to ensure no involvement of iconic memory in performance. The second stimulus could be identical (same shape and same orientation), an orientation transformation (either a mirror-image or a 180º plane-rotation), or a fully-different one (different shape and different orientation). Children were asked to decide whether the second stimulus was the same or not as the first (through key pressing) based on a specific criterion depending on the task.

In the shape-based task, children should respond *same* if the second stimulus had the same shape as the first, regardless of orientation, and hence, identical, mirror-image, and plane-rotation shapes required a *same* response, and *different* on fully-different trials. Orientation processing was thus irrelevant to successful performance. In the orientation-based task, children should respond *same* only if the second stimulus was an exact match of the first; otherwise they should respond *different*, that is, for mirror-image, plane-rotation, and fully-different pairs. Orientation processing was thus critical to successful performance. The shape-based task was performed first to ensure that accuracy was not affected by orientation costs that could have occurred if the orientation-based task was performed first. The two tasks were performed on two types of material: asymmetrical geometric shapes, a novel material for all children and letters (reversible and non-reversible). Each task was performed first for geometric shapes to ensure that any spillover effect would not be due to prior performance on letters.

Children sat at a distance of ~50 cm of the computer screen (resolution: 1366 x 768 pixels; refresh rate: 60 Hz). Before each task children were asked to place their fingers over the keys without pressing them so they could be faster when answering. Instructions were given orally and six demo-trials with black and white drawings of familiar images (e.g., a cat) were presented. Next, to ensure children understood the task, they performed 12 practice trials, six with familiar images and six with the experimental material, half of them leading to a *same* response. If they failed more than six practice trials, or more than half of the practice trials with the experimental material, the practice trials were repeated. In each trial, a cross was displayed on the centre of the screen for 1 s after which the first stimulus was presented at the same location for 1 s, followed by a 500 ms mask, and finally the second stimulus was presented at the same location until response or, if no response was given, for a maximum of 2.5 s, after which another trial begun. On each task, half of the trials should be answered *same*. Trials were controlled by E-Prime 2, and accuracy and response time were registered in every trial.

On each task children performed 108 trials with geometric shapes (in the shape-based task 54 trials were fully-different, 18 identical, 18 mirror-image, and 18 plane-rotation trials; in the orientation-based task 54 trials were identical, 18 fully-different, 18 mirror-image, and 18 plane-rotation trials) and 96 trials with letters, half of them with reversible letters, the other half with non-reversible letters (in the shape-based task 48 trials were fully-different, 16 identical, 16 mirror-image, and 16 plane-rotation trials; in the orientation-based task 48 trials were identical, 16 fully-different, 16 mirror-image, and 16 plane-rotation trials).

2.2.3. Training – tablet games

Training was implemented as one of two games - draw and contact - developed for the present study and played on a tablet using the touch interface on which children used their finger to play with letters. In both, visuomotor training was combined with letter exposition but in none of the games the letter names were ever presented in order to ensure that only motor aspects would assist in the emergence of mirror-image discrimination.

The two games were created with Stencyl platform (Version 3.4.0 beta2 - build 8868). The games had the same storyboard, characters, and structure, as shown in Fig. 2, and used the same six letters. Children were trained in two symmetrical letters, i.e., o; x, two reversible letters, i.e., d; p, and two non-reversible letters, i.e., e; k. We ensured that the three types of letters had similar motor complexity, calculated as in Changizi et al. (2006; see Table 4), $F < 1$. The letters were created with PowerPoint, Calibri font, size 800, white colour with an outline of 10-point thickness, in orange: RGB 228, 108, 10, and imported to the game platform.

The games were designed to allow and ensure that children showed the intended motor behaviours, i.e., that they correctly traced the letters (in the draw game) or moved the letters along the defined path (in the contact game), preventing them to persist on incorrect movements. Therefore, the games controlled that children started the tasks, and the second stroke of a letter (in the draw game), within the defined time, and that they started the tasks at the right point, i.e., they should press the coloured marker on the letter (henceforth *task-marker*); control regions were defined (as shown on Fig. 3) to ensure that children did not go backwards, i.e., the task-marker should not cross twice the circular control regions defined, and that children did not raise their finger before the end of the task (or of the first letter stroke, for letters with more than one stroke in the draw game), i.e., the task-marker had necessarily to enter the rectangular control regions defined at the end of letter strokes and moving paths before children raised the finger.

The games complied with the lack of precision of human movements, as mentioned in the Introduction (Chapter 1). Therefore, they controlled children's accuracy in task performance, i.e., whether children kept the task-marker inside the letter outline (draw game) or on the moving path (contact game). To this aim, as shown in Fig. 3, polygonal control regions were defined outside the letter or moving path, which the task-marker should not enter, and the circle control regions defined should be necessarily crossed by the task marker.

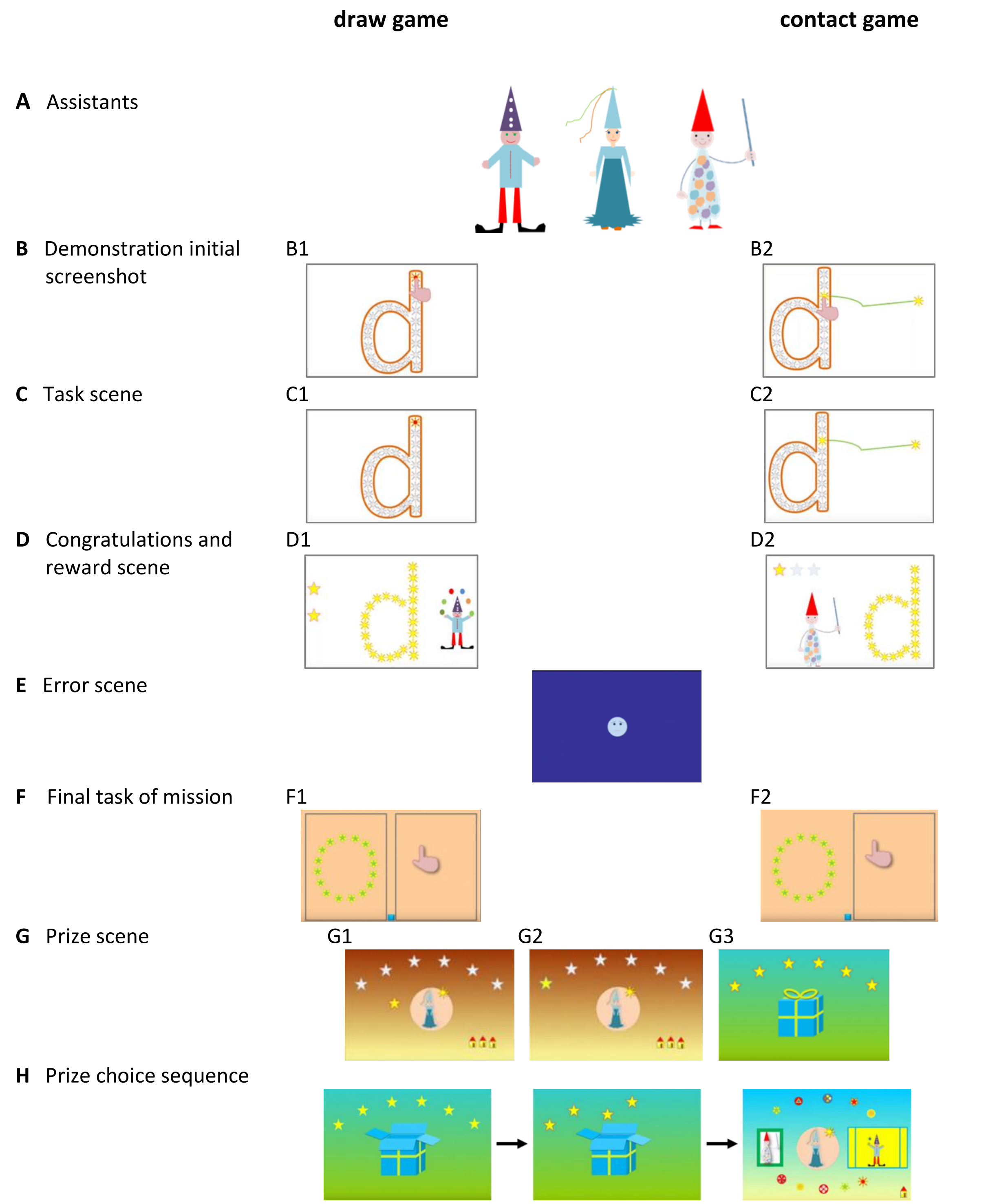

Figure 2 Characters and scene screenshots in the games draw and contact.

(A) From left to right: the clown, the princess, and the magician. (B1) Tracing task demonstration (B2) Moving task demonstration (C1) Tracing task scene (C2) Moving task scene (D1) All stars coloured, i.e., the two tasks of the mission were completed. (D2) One coloured star, two grey stars, i.e., one task was completed and two had yet to be performed. (F1) Copying task (F2) Free-moving task (G1) One coloured star outside the six-star array, i.e., no tasks were completed. (G2) One coloured star, i.e., only one task was completed. (G3) All stars coloured, i.e., all tasks were completed. (H) From left to right: present opened by the child; stars being put inside the present by the child; prize choice screen displayed after all stars were inside the present.

Table 4 Motor complexity, number of strokes (NS) and number of lifts (NL) for the trained letters

Letter	Letter type	Motor Complexity (NS+NL)	NS	NL
o	Symmetrical	1	1	0
x	Symmetrical	3	2	1
d	Reversible	3	2	1
p	Reversible	3	2	1
e	Non-reversible	2	2	0
k	Non-reversible	4	3	1

Note: Motor complexity was calculated cf. Changizi et al. (2006), as the sum of the number of strokes of each letter (i.e., the number of segments between two points), and the number of lifts necessary to produce it (i.e., the number of times the pen is lifted to start another segment).
ANOVAs were run separately on the number of strokes and on the number of lifts; no effect of letter type was found, $F(2, 3) = 1.50$, $p = .35$, and $F < 1$, respectively.

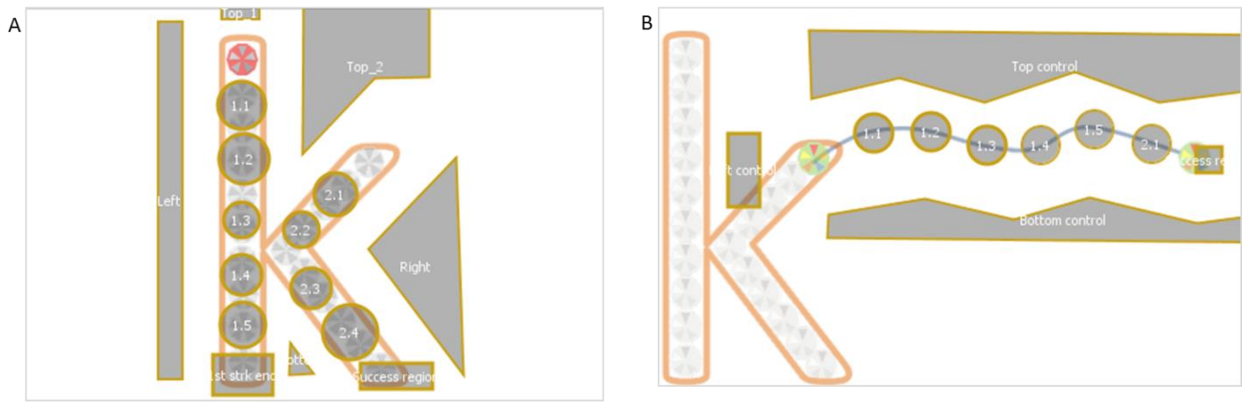

Figure 3 Example of control regions defined in the games. (A) Tracing task in the draw game (B) Moving task in the contact game

Note: Control regions were not visible in the task scenes.
Polygonal regions outside the letter or path and circular regions: defined to comply with movements' lack of precision; circular regions used also to control movement direction.
Rectangular regions at the bottom of letter strokes (on A), and at the right end of the path (on B): defined to control task conclusion (and first letter stroke conclusion, in the draw game), and lifting of the finger.

When children failed to perform the correct motor actions, an error was made and the game proceeded to the error scene. As described in Table 5, seven types of errors, five of which common to both games, could occur. According to the error made, specific feedback was given on the error scene. This way the game interacted with the child so that she/he could learn how to avoid errors and improve her/his performance and movements' accuracy along sessions without the experimenter's involvement.

Table 5 Description of the errors controlled by the games, error type, and game in which they occur.

Error description	Error type	Game
Not starting the task after 10 s	no-start	draw | contact
Not starting the task at the right point	wrong-start	draw | contact
Raising the finger before finishing the task[a]	raising-finger	draw | contact
Going backwards	going-back	draw | contact
Going out the letter outline (draw game) or the moving path (contact game)	going-out	draw | contact
Trying to go in the wrong direction inside the letter outline[b]	wrong-way	draw
Not starting the next stroke of the letter after 6 s	no-next	draw

[a] In draw game: raising the finger before finishing the letter or stroke; in contact game: raising the finger before reaching the end of the path. [b] In letters d, p, k, and x: to go into the next stroke before finishing the actual one; in letter e: to go into the second stroke when starting the tracing; in letter o: to go in clockwise direction.

The games were developed, based on Nielsen (1993), to be easy to learn and playful. First, to ensure children could easily learn to play the games, all necessary information was provided, demonstrations were shown, and regular feedback was given. Task scenes, as well as demonstrations, did not have unnecessary elements to ensure that children were exclusively focused on what was relevant to the tasks. All instructions were child-appropriate and presented orally given that children were preliterate. Second, to ensure children would find the games playful and entertaining, colourful backgrounds and interactive elements were present along the game. Also, at the beginning of the game, children were introduced to three assistants and chose one to help them throughout the game: clown Barnabé from the Rainbow circus, princess Filipa from the Rainbow kingdom, and Arthur the magician, from the Magic place of the Rainbow kingdom (see Fig.2). These animated characters interacted with children helping them with instructions and feedback. The voices of the assistants and the narrator (who introduced the game) were from three European-Portuguese native speakers (two females) and were recorded in a sound-proof room, edited using Adobe audition[1] and Audacity (free, open source software; version 2.1.2[2]) and then integrated into the games.

The two games were structured in challenges which comprised two or three missions to be accomplished. By using challenges and missions, that is, elements that are usually found in games and cartoons, our games adopted a language to which children were already familiar with, promoting their engagement. On each challenge, children had to complete two or three missions. Each mission concerned one of the six letters, and comprised, in turn, four or three tasks (respectively) to be performed on that letter. In the draw game children performed tracing and copying tasks, while in the contact game children performed moving (along a predefined path) and free-moving tasks. When the challenge comprised two missions, children had to perform three tracing and one copying task or three moving and one free-moving task in each mission; when it comprised three missions, they had to perform two tracing and one copying task or two moving and one free-moving task in each mission. In this way, children were presented with six tracing/moving tasks in all challenges. Table 6 presents the game structure and letter order along training, which was predefined and the same in the two games.

In both games, each challenge started with the title scene and after 3 s a brief explanation of the game was given by the narrator. Next, children were asked to choose their

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[1] http://www.adobe.com/pt/products/audition.html
[2] http://www.audacityteam.org/

assistant, who introduced himself/herself[3], explained the actions to be performed during the game, and announced the rewards and the final prize that would be exchanged for the stars that children would collect along the challenge. Then, the assistant announced they had one challenge to accomplish with a number of missions. On each mission, each tracing or moving task started with a demonstration, introduced by the assistant (e.g., "First, I will show you how a real clown does it!"), showing children how to perform the task. The demonstration scene presented all the elements to be found in the task scene, plus one hand with a pointing finger in the marker to be pressed, i.e., the task-marker (see Fig. 2): in the draw game the pointing finger dragged the task-marker along the letter, turning the grey markers into coloured ones as it went over them; on the contact game the pointing finger dragged the letter until the end of the path. Next, the task scene was presented and the assistant prompted the child to perform the task: "It's your turn now!" (voice-over, to ensure children kept their attention on the task). In these tasks children always received feedback on their performance. Only after the successful completion of each task a rewarding chiming sound[4] was played and the assistant congratulated the child announcing that she/he had won a star. This coloured and blinking star was displayed while the remaining stars not yet won (if any) were in grey colour, as shown in Fig. 2D. If children made an error the task was aborted and the error screen shown in Fig. 2E was presented with corrective feedback given in a neutral voice[5].

After successful completion of the first task (or after completion of the second task for those missions with four tasks), the demonstration was presented again, and children were prompted to perform the next task. After successful completion of all tracing/moving tasks in the mission, the game proceeded to the *final* task, i.e., the copying task in the draw game or the free-moving task in the contact game. When children made an error, the task was aborted

[3] e.g., "Hello! Hello! I am the clown Barnabé and I come from the Rainbow Circus especially to play the letter game with you!"
[4] Sound from Stencyl.
[5] The voice used in the corrective feedback differed from that of the assistants in order to avoid that children associated the assistant with the error events.

and the demonstration was presented again. Children had then a second chance to complete the task; however, if they made an error on this second attempt the game would proceed to the final task of the mission. This way, only two consecutive errors could be done in a mission as shown in Fig. 4. This criterion was defined to minimize children's frustration for not having attained the objective of completing the task successfully.

In the final task, the assistant announced that in order to complete the mission the child had to copy or move the letter. As shown in Fig. 2F, in this task, an empty frame appeared on the right-side of the screen with a small hand moving inside it, while the assistant explained the task to be performed: in the draw game, children should copy the letter presented in the left-side frame in the right-side empty frame (when children pressed and dragged their finger inside the empty frame the movement was reproduced with coloured markers); in the contact game, they should move the letter into the right-side frame following whatever path they wanted (no reproduction of the movement was presented). Next, the assistant wished the child a "good task". When the child finished the task, she/he pressed the blue square at the bottom of the screen (as explained by the assistant) and in the next scene the assistant thanked the child while a star was displayed. Therefore, independently of children's performance in the final task, positive feedback was always provided without any corrective instruction.

Table 6 Challenges, missions, tasks, and letter order in the games.

Challenge	**Mission 1**	**Mission 2**	**Mission 3**
	Tasks	Tasks	Tasks
1.1 ; 1.2	o | o | o | [o]	x | x | x | [x]	
2.1 ; 2.2	e | e | e | [e]	k | k | k | [k]	
3.1 ; 3.2	d | d | d | [d]	p | p | p | [p]	
4.1 ; 4.2	o | o | [o]	x | x | [x]	e | e | [e]
5.1 ; 5.2	k | k | [k]	d | d | [d]	p | p | [p]
6.1 ; 6.2	o | o | o | [o]	x | x | x | [x]	
7.1 ; 7.2	e | e | e | [e]	k | k | k | [k]	
8.1 ; 8.2	d | d | d | [d]	p | p | p | [p]	
9.1 ; 9.2	o | o | [o]	d | d | [d]	e | e | [e]
10.1 ; 10.2	k | k | [k]	d | d | [d]	p | p | [p]
11.1 ; 11.2	x | x | x | [x]	e | e | e | [e]	
12.1 ; 12.2	k | k | k | [k]	d | d | d | [d]	
13.1 ; 13.2	p | p | p | [p]	o | o | o | [o]	
14.1 ; 14.2	x | x | [x]	e | e | [e]	k | k | [k]
15.1 ; 15.2	d | d | [d]	p | p | [p]	o | o | [o]
16.1 ; 16.2	e | e | e | [e]	k | k | k | [k]	
17.1 ; 17.2	d | d | d | [d]	p | p | p | [p]	
18.1 ; 18.2	o | o | o | [o]	x | x | x | [x]	
19.1 ; 19.2	e | e | [e]	k | k | [k]	d | d | [d]
20.1 ; 20.2	p | p | [p]	o | o | [o]	x | x | [x]

Note: Each letter corresponds to one task. Letters in brackets correspond to copying or free-moving tasks; all the other letters correspond to tracing or moving tasks.

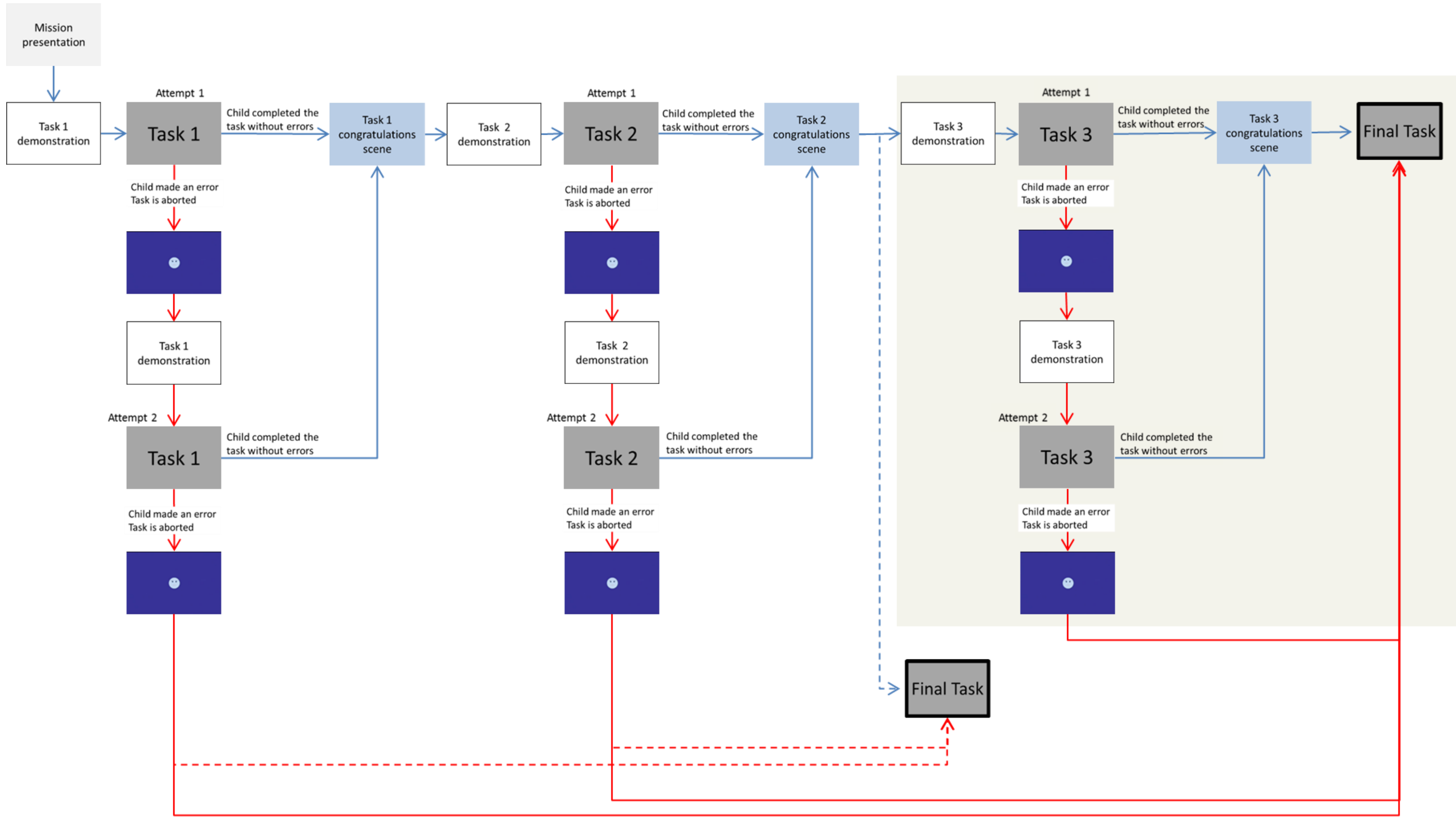

Figure 4 Possible sequences of events in missions with two and three tracing/moving tasks and one final copying/free-moving task.

Note: Red lines: flow of events when errors are made; dashed lines: final sequence of events when a mission has two tracing/moving tasks. Grey area: events occurring only in missions with three tracing/moving tasks.

Children could make a maximum of three errors in missions with two tasks, and four errors in missions with three tasks, but only two consecutive errors in a mission.

The challenge ended when all missions were completed (independently of children's success). Next, in the prize scene, the stars won along the challenge were displayed in colour, as shown in Fig. 2. Note that at least one star was awarded even when the child had not successfully completed any of the six tasks. In this case, the coloured star was displayed in a different place than those stars awarded for successful performance. If the child had not won all the six stars (i.e., one for each tracing or moving task), the assistant regretted it, comforted the child (e.g., "Next time (…) all clowns in the Rainbow Circus will be on your side, giving you support so it goes better!"), and presented the prize. If the child had successfully accomplished all missions (i.e., the six tracing or moving tasks), then six coloured stars were displayed. At the same time, the assistant effusively congratulated the child asking her/him to press the gift to open it, put all stars inside it, and see what would happen. Next, the three possible prizes were displayed (Fig. 2H) and the assistant asked the child to choose one of them (only when all tasks were successfully completed the child could freely choose the prize[6]): i.e., hearing a song (free songs available in the Pink Fong app music store from Smartstudy[7], available at the Google Play Store), playing a ludic game (LEGO® DUPLO® Train, LEGO® DUPLO® Food[8], and the mini-games from My Boo, a virtual pet mobile app from Tapps Games[9], all available at the Google Play Store) or watching a short movie (three Shawn the Sheep short movies, Babysitting Timmy, Stomp, and Video arcade, from Aardman Animations[10] and one Bernard short movie, The Vending Machine, from RG Animation Studios[11], available on YouTube). The assistant instructed the child to ask the experimenter for the prize and the game stopped.

[6] We ensured that the games, songs, and movies used as prizes were age appropriate.
[7] https://about.pinkfong.com/en/
[8] http://www.lego.com/en-us/duplo/apps
[9] http://tappsgames.com/
[10] http://www.shaunthesheep.com/
[11] https://en.wikipedia.org/wiki/Bernard_(TV_series); http://englishbrb.adnstream.com/canal/Bernard

Before the study, the two games were tested with three 4- to 8-year-old children (2 girls) that were not part of the study; these children were observed while playing. We thus ensured that 4- to 8-year-old children were able to understand the tasks, to perform them successfully, and that they enjoyed playing the games[12].

In the present study, each child was trained in only one of the games during twenty 20 min daily sessions (with two challenges per session) in a quiet room at children's schools (either individually or in groups of 2-3 children) and supervised by the experimenter. Children were advised to pay attention to the game and to carefully listen to all instructions so that they could win all the stars. No indication was given about the hand/finger they should use, and the name of the letters trained was never mentioned. At the end of each session children were also rewarded with a sticker, and at the end of the first training week they received a sticker book.

Three tablets were used: two ASUS ZenPad C 7.0, 189 mm x 108 mm x 8.4 mm dimensions, 265 g weight, 7" IPS LCD capacitive touchscreen, 16M colours, 1024 x 600 pixels resolution with ~170 ppi pixel density, Android V5.0.2 (Lollipop) operating system, Intel® Atom™ x3-C3200 chip with a quad-Core 64-bit CPU, up to 1.1 GHz, and a Mali-450 MP4 graphics processor, 2 GB RAM, and 16 GB internal memory; one Samsung Galaxy SM-T530, 243.4 mm x 176.4 mm x 8 mm dimensions, 487 g weight, 10,1" TFT capacitive touchscreen, 16M colours, 1280 x 800 resolution with ~149 ppi pixel density, Android V5.0.2 (Lollipop) operating system, Qualcomm Snapdragon 400 chip with a quad-core 1.2 GHz, 32 bit CPU, and an Adreno 305 graphics processor, 1.5 GB RAM, and 16 GB internal memory.

[12] Note that the children that participated in the present study were also enthusiastic about the games. They easily learned how to play and while playing they showed enjoyment: e.g., they regularly nodded or answered when the assistant asked "Do you want to earn another star?"; some children celebrated when winning a star or all the six stars, shouting, getting up the chair, raising their arms.

Game sessions were screen recorded with Telecine[13] for further collection of the number of errors in each mission by letter-type and error-type. At the end of training, children had performed 20 sessions, 40 challenges, and 96 missions, with a maximum of 240 tracing or moving tasks (80 x 3 letter-type; please note that if children made one error on each of the two attempts to complete the first task on all missions[14] the maximum number of presented tasks would be 96 tasks: 32 x 3 letter-type) and 96 final (copying or free-moving) tasks (32 x 3 letter-type).

2.2.4. Training – performance measure index

The training was designed so that children would learn the correct motor actions for each letter by training them the most number of times with the least number of errors as possible, that is, by completing as many tracing/moving tasks at first attempt (final tasks were not considered because they had no control for errors). Given that on each attempt to complete a task, the letter was viewed by the child, then the number of attempts corresponds to the number of times that children viewed the letter and is hereafter referred as *number of views*.

Therefore, to analyse children's performance in the games, we devised a *performance index* that emphasised the importance of completing all tasks in a mission and without errors, even if in some cases fewer tasks were completed overall. For instance, completing two tasks without errors in a two-task mission would lead to a higher performance index indicating better performance than in two situations such as: (i) completing two tasks in a three-task mission because in this case children would still have difficulty in performing the correct motor actions and were not able to perform all tasks of the mission, or (ii) completing three tasks in a three-task mission after two errors (one error on two tasks) because although able to

[13] https://play.google.com/store/apps/details?id=com.jakewharton.telecine&hl=pt_PT

[14] As aforementioned in the main text, after one error on each of the two possible attempts to complete a task the game proceeded to the final task of the mission, not showing other tasks not yet performed.

complete all tasks of the mission, children had to view the letter five times to be successful (see Table 7).

The performance index is computed with the number of tasks successfully completed in each mission, *NTm*, the number of errors made in each mission, *NEm,* and the number of views in each mission, *NVm*. Note that, as aforementioned, when a task was completed after one view, it was completed with no errors; when it was completed after two views, it was completed with one error; and when the task was not completed, then two errors were made in the second view of the task (for examples, please see Fig. 5). Thus, *NVm* is calculated as follows

$$NVm = NTm + NEm \qquad (1)$$

When dividing all terms of (1) by *NVm* we obtained:

$$1 = \frac{NTm}{NVm} + \frac{NEm}{NVm} \qquad (2)$$

After rearranging (2) we got:

$$1 - \frac{NEm}{NVm} = \frac{NTm}{NVm} \qquad (3)$$

Finally, we multiplied both members of (3) by *NTm* and obtained:

$$NTm\left(1 - \frac{NEm}{NVm}\right) = \frac{NTm^2}{NVm} \qquad (4)$$

in which the left member of (4) will be the *performance index P*, used to assess training efficacy:

$$P = NTm\left(1 - \frac{NEm}{NVm}\right) \qquad (5)$$

Please note that the term $1 - \frac{NEm}{NVm}$ in (5) expresses the weight given to the number of successfully completed tasks in the mission, and is a function of the number of errors and the number of views on that mission. When no errors were made, $1 - \frac{NEm}{NVm} = 1$, and hence, performance is equal to the number of tasks successfully completed. All possible values for *NVm* and *P* are shown in Table 7.

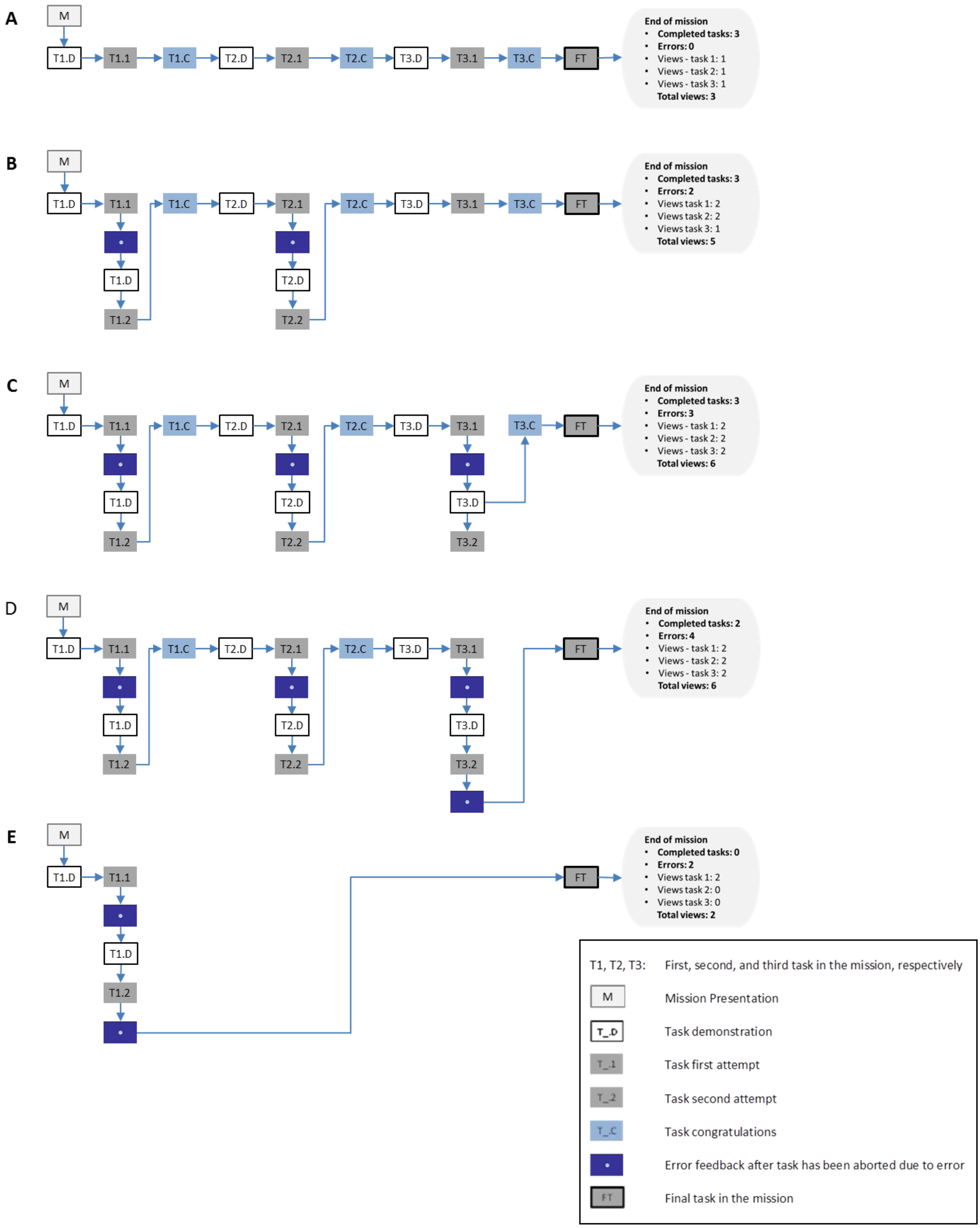

Figure 5 Examples of outcomes regarding the number of completed tasks, errors, views, and total number of views in missions with three tasks.

Please note: In A, B, and C the same number of tasks were completed however, in B and C the tasks were completed with two and three errors, respectively, while in A no errors were made. In C and D were made more errors than in E however in E no tasks were completed. In all cases the total number of views equals the sum of completed tasks and errors.

Table 7 Values for (A) number of views, and (B) performance index, for missions with three and two tracing/moving tasks.

(A) **Number of views (attempts)**

	Total no. of completed tasks in the mission	Total no. of errors in the mission: 0	1	2	3	4
Missions with three tracing/moving tasks	0	—	—	2	—	—
	1	—	—	3	4	—
	2	—	—	4	5	6
	3	3	4	5	6	—
Missions with two tracing/moving tasks	0	—	—	2	—	
	1	—	—	3	4	
	2	2	3	4	—	

(B) **Performance index**

	Total no. of completed tasks in the mission	Total no. of errors in the mission: 0	1	2	3	4
Missions with three tracing/moving tasks	0	—	—	0.00	—	—
	1	—	—	0.33	0.25	—
	2	—	—	1.00	0.80	0.67
	3	3.00	2.25	1.80	1.50	—
Missions with two tracing/moving tasks	0	—	—	0.00	—	
	1	—	—	0.33	0.25	
	2	2.00	1.33	1.00	—	

Note: '—' denotes an impossible value, e.g., it is impossible to complete only one task successfully in a mission and have made only one error.

3. Results

For the independent tasks and the training, we examined the main effects of the independent variables or *factors*, specifically, how the game (the between-participants[15] factor), the within-participants[16] factors manipulated in each specific task, and their interaction (i.e., how a factor modulated the impact of another) affected the outcome (i.e., the measurement variable used in each task, as described in Table 8) with mixed designs for which *F*-statistics and *p*-values obtained in the *analyses of variance* (ANOVAs) run are reported. Note that the conventional level of statistical significance was applied (i.e., $p = .05$). However, for theoretically-driven hypotheses, we still performed comparisons even when these effects were not significant ($p > .05$).

First, we analysed the results at pre-training in each task, in order to ensure that before training the two groups of children, each assigned to one game, were matched in their performance in these tasks. Therefore, any impact of training found at post-training would not be due to differences already existing before the training. Next, we examined children's performance in the games to test our hypotheses on the role of the visuomotor representations of letters on mirror discrimination and to examine whether learning had occurred during training. Finally, to explore transfer effects, i.e., the impact of training on independent tasks, we explored the results at post-training on these tasks. To this aim, we examined children's performance in each task with the additional within-participant factor *testing-phase* (pre-training vs. post-training). We will thus present the results of ANOVAs for each task in the pre-training phase, then the results regarding performance in the games along training, and finally the results in each task considering the difference between pre- and post-training phases. Given that three children from the 14 initially selected did not complete the training

[15] Between-participants factor - a factor for which each group of participants is associated with one of its levels)

[16] Within-participants factors - factors for which participants did more than one trial, therefore several measures were taken from each participant.

phase (see Chapter 2), the analyses here presented refer to the final sample (N = 11). We still checked that the same pattern of results was found in pre-training phase with the original sample (N = 14). Whenever discrepancies were found between these two samples, statistical results for the original sample are reported in footnote.

Table 8 Outcomes, factors, and levels used in the adopted mixed designs by task. (A) within-participants factors; (B) between-participants factors.

A

Tasks	**Outcomes**	**Within-participants factor**	**Levels**	**Within-participants factor**	**Levels**
Letter Knowledge	Number of letters correctly produced	Task	naming; recognition		
		Case	uppercase; lowercase		
4AFC	Accuracy	Letter-set	trained; untrained	Letter-set	trained; untrained
		Letter-type	non-reversible; reversible; symmetrical	Letter-type	non-reversible; reversible
				Orientation-distractor	mirror-image; plane-rotation
Same -Different Geometric shapes	Accuracy Response time	Task	shape-based; orientation-based		
		Trial-type	fully-different; identical; mirror-image; plane-rotation		
Same-Different Letters	Accuracy Response time	Task	shape-based; orientation-based		
		Letter-type	non-reversible; reversible;		
		Trial-type	fully-different; identical; mirror-image; plane-rotation		

B

		Between-participants factor	**Levels**
All tasks		Game	contact; draw

Note: The effect that one factor has on the outcome is averaged across all levels of the other factors being considered.

3.1. Pre-training results

3.1.1. Letter knowledge

Before training, we analysed the impact of game (draw, contact: between-participants), task (naming, recognition: within-participants) and letter case (upper-case, lower-case: within-participants) and their interaction in a 2 x 2 x 2 mixed ANOVA run on the mean number of letters correctly produced by children. No significant effects were found for game, $F(1, 9) = 2.49$, $p = .149$, for the interaction between game and case, $F(1, 9) = 3.10$, $p = .112$, and for the three-way interaction between game, task, and case, $F < 1$, demonstrating that the two groups of children were well matched on their letter knowledge in the two letter cases and for the two tasks. Although the interaction between game and task, $F(1, 9) = 4.90$, $p = .054$[17] was only marginally significant, to ensure that the two groups were adequately matched, we directly compared them on each task: no significant differences between children to be assigned to each game were found on letter naming, $F(1, 9) = 3.37$, $p = .100$, or recognition, $F(1, 9) = 1.63$, $p = .234$. Children in the contact game were only numerically, but not significantly, better than children in the draw game in letter naming, $M_{contact} = 8.50$, $SEM = 1.51$, $M_{draw} = 4.75$, $SEM = 1.38$, and recognition, $M_{contact} = 7.40$, $SEM = 1.44$, $M_{draw} = 4.92$, $SEM = 1.31$. Nonetheless, this numerical difference was not problematic because if anything it would run against our hypothesis. Note that a positive association between letter knowledge and mirror-image discrimination abilities was previously reported (Fernandes et al., 2016), and hence, children with higher letter knowledge before training might be more sensitive to mirror images differences, which in the present case would be those assigned to the control, contact game.

The main effect of case, $F(1, 9) = 56.38$, $p < .001$ was significant. Children knew more upper-case than lower-case letters, in line with prior evidence (e.g., Worden & Boettcher, 1990; Smythe, Stennett, Hardy, Wilson, 1970). The main effect of task was not significant, $F(1, 9) = 2.66$, $p = .137$, nor the interaction between task and case, $F(1, 9) = 4.57$, $p = .061$.

3.1.2. Four-alternative forced-choice task

For the 4AFC task, we first analysed the impact of game on letter-set (trained vs untrained, a factor that would only be relevant after training) and letter-type (non-reversible;

[17] For $N = 14$, the interaction between game and task, $F(1, 12) = 1.66$, $p = .223$ was not significant.

reversible; symmetrical) on mean accuracy (arcsine transformed[18]) in a mixed 2 x 3 x 2 ANOVA. Demonstrating that the two groups of children to be assigned to each game were adequately matched, neither the main effect of game, $F < 1$, nor any interaction with it was significant: Game x Letter-type, $F(2, 18) = 1.29$, $p = .299$, Game x Letter-set, $F < 1$, Game x Letter-set x Letter-type, $F < 1$. The main effect of letter-type was significant, $F(2, 18) = 25.69$, $p < .001$, as children had better performance for symmetrical letters (M = 90.14%, SD = 0.041) than for non-reversible (M = 64.15%, SD = 0.047), $F(1, 9) = 57.60$, $p < .001$, and reversible letters (M = 56.54 %, SD = 0.055), $F(1, 9) = 26.10$, $p < .001$, with similar performance for the two latter letter types, $F(1, 9) = 1.64$, $p = .233$. This pattern of results agrees with the high-sensitivity of the visual system to symmetry (Wagemans, 1997), which in turn is a common property of written scripts (e.g., Changizi et al., 2006). Noteworthy, children were quite able to perform the task, with performance significantly above chance (i.e., 25% correct) for the three letter types (non-reversible letters, $t(10) = 8.48$, $p < .001$; reversible letters, $t(10) = 5.90$, $p < .001$, symmetrical letters, $t(10) = 16.38$, $p < .001$) but significantly below ceiling, i.e., 100% accuracy (non-reversible letters, $t(10) = -7.90$, $p < .001$; reversible letters, $t(10) = -7.93$, $p < .001$, symmetrical letters, $t(10) = -2.55$, $p = .015$), showing that children had still room to improve on this task. The main effect of letter-set, $F < 1$, and the interaction between letter-set and letter-type, $F(2, 18) = 1.33$, $p = .289$, were not significant, given that children had not started the training yet.

Next, given that for asymmetrical letters the distractors included an orientation distractor, that is, a mirror image or a plane rotation of the target letter, we examined whether the type of orientation distractor affected children's decision with a mixed 2 x 2 x 2 ANOVA on mean accuracy (arcsine transformed) with game, letter-set, letter-type (reversible; non-reversible), and orientation-distractor (mirror-image; plane-rotation). Again, the results

[18] arcsin transformation (i.e., arcsin of the square root of data) is used to normalise binomial distributions of data.

showed that the two groups were adequately matched in their performance: Game, Game x Orientation-distractor, and Game x Letter-type x Orientation-distractor, all *F*s < 1; Game x Letter-set x Orientation-distractor, $F(1, 9) = 3.38$, $p = .099$; Game x Letter-set x Letter-type x Orientation-distractor, $F(1, 9) = 1.39$, $p = .268$. As in the previous analysis, Game, Game x Letter-set, Game x Letter-set x Letter-type (all *F*s < 1), and Game x Letter-type ($F(1, 9) = 1.53$, $p = .247$) were not significant.

Interestingly, in line with the mirror invariance of visual object recognition (e.g., Bornstein et al., 1978; Dehaene, Nakamura, et al., 2010), children's performance was affected by orientation contrast of the distractors, $F(1, 9) = 16.16$, $p = .003$, with worse performance when the orientation distractor was a mirror image than a plane rotation. This difficulty with mirror-image distractors was not affected by letter-set, letter-type, or the combination of these factors (Letter-set x Orientation-distractor, $F(1, 9) = 2.71$, $p = .134$; Letter-type x Orientation-distractor, $F < 1$; Letter-set x Letter-type x Orientation-distractor, $F(1, 9) = 1.01$, $p = .341$). The main effects of letter-type, $F\ (1,9) = 1.23$, $p = .297$, and letter-set, $F < 1$, and the interaction between them, $F\ (1,9) = 1.23$, $p = .332$, were not significant: children's accuracy was similar for reversible and non-reversible letters either from the trained or untrained set.

3.1.3. Same-different tasks

We examined the impact of game, task (shape-based; orientation-based), and trial (fully-different; identical; mirror-image; plane-rotation) on mean accuracy on these tasks (arcsine transformation of proportion of correct responses) and on the *response times* for correct answers (*RT*s, logarithmic transformed[19]; after trimming of outliers 2.5 *SD* above or below the grand mean for each participant by material and task; < 2% data excluded). To ensure that children were adequately matched before training, two mixed ANOVAs were run

[19] logaritmic transformation (here calculated as natural logaritm of RTs), is used normalise the distribution of response times.

separately for each visual category: geometric shapes and letters. For letters, the additional within-participants factor letter-type (reversible; non-reversible) entered the ANOVAs.

3.1.3.1. Geometric shapes

The main effect of game was not significant on accuracy or RTs, both Fs < 1, nor any interaction with game (Game x Trial: accuracy, $F(3, 27) = 1.90$, $p = .154$, RTs, $F(3, 27) = 1.21$, $p = .324$; other interactions: accuracy and RTs, all Fs < 1). Therefore, before training, the two groups of children to be assigned to each game were adequately matched on performance in the shape-based and the orientation-based tasks for geometric shapes. The main effect of task was not significant on accuracy, $F < 1$, or RTs, $F(1, 9) = 3.85$, $p = .081$.

The only significant effect found on accuracy was the main effect of trial, $F(3, 27) = 3.55$, $p = .027$ (for RTs[20], $F(3, 27) = 1.73$, $p = .184$). Children were significantly less accurate on mirror-image trials than on the easiest fully-different and identical trials ($F(1, 9) = 10.95$, $p = .009$, $F(1, 9) = 8.03$, $p = .020$, respectively). No significant differences were found on accuracy between plane-rotation and fully-different $F(1, 9) = 3.62$, $p = .090$, or identical trials, $F(1, 9) = 3.73$, $p = .085$. Children had similar accuracy on mirror-image and plane-rotation trials, F <1, and on identical and fully-different trials, F <1.

The main effect of trial was not modulated by task, neither on accuracy, $F(3, 27) = 1.01$, $p = .402$, nor RTs, $F < 1$.

3.1.3.2 Letters

The main effect of game on accuracy and RTs (both Fs < 1), and the interaction Game x Task on accuracy, $F < 1$, and RTs $F(1, 9) = 3.76$, $p = .084$ were not significant, as found for geometric shapes. Thus, the two groups of children were adequately matched in performance. No other significant interactions with game were found, as the statistical pattern of results reported in Table 9 shows, indicating the proper match of the two groups in same-different

[20] For $N = 14$ there was an effect of trial both on accuracy, $F(3, 36) = 5.13$, $p = .005$, and on RTs, $F(3, 36) = 3.59$, $p = .023$.

tasks. As for geometric shapes, the main effect of task was not significant on RTs, $F(1, 9) = 4.93$, $p = .053$, or accuracy, $F < 1$. The main effect of letter-type was neither significant (accuracy: F(1, 9) = 1.05, p = .333; RTs, F < 1) nor interacted with other factors: Letter-type x Task, accuracy, F(1, 9) = 2.23, p = .170, RT, F < 1; Letter-type x Trial, accuracy, F(3, 27) = 1.58, p = .217, RTs, F < 1; Letter type x Task x Trial, accuracy and RT, Fs < 1, agreeing with prior findings (Fernandes et al., 2016).

Table 9 *F* and *p* values for same-different tasks with letters at pre-training regarding non-significant interactions, on accuracy and RTs, not presented in the text (*df* - degrees of freedom).

Interaction	Outcome	*df*	*F*	*p*
Game x Letter-type	accuracy	1, 9	< 1	
	RT		1.48	.255
Game x Trial	accuracy	3, 27	1.74	.183
	RT		< 1	
Game x Task x Letter-type	accuracy	3, 27	< 1	
	RT		< 1	
Game x Task x Trial	accuracy	3, 27	< 1	
	RT		1.01	.403
Game x Letter-type x Trial	accuracy	3, 27	2.17	.114
	RT		< 1	
Game x Task x Letter-type x Trial	accuracy	3, 27	< 1	
	RT		1.40	.263

The main effect of trial was not significant, $F(3, 27) = 1.74$, $p = .183$ (for RTs, $F < 1$), although it was significant in the initial sample[21], which may suggest that this non-significant result is due to the small size of the sample. As the interaction between task and trial was marginally significant on accuracy, $F(3, 27) = 2.86$, $p = .055$[22] (not on RTs, $F < 1$), we explored it. In the shape-based task we checked whether there was a mirror cost, which was not the case, as the difference between performance (accuracy and RTs) on mirror image and identical trials was not significant (accuracy, $F(1, 9) = 2.79$, $p = .130$; RT, $F < 1$). The mirror

[21] For $N = 14$ the main effect of trial was significant $F(3, 36) = 3.40$, $p = .028$ for accuracy, but not for RTs, $F < 1$. Children in both groups were less accurate on mirrored trials than on fully-different trials $F(1, 12) = 6.30$, $p = .027$, but response times did not differ, $F < 1$.

[22] For $N = 14$, $F(3, 36) = 2.68$, $p = .061$.

invariance here found for letters, seems to depend on children's low letter knowledge, given that Fernandes et al. (2016) have shown that the more letters children know, the stronger is the mirror cost shown by pre-literate children. Regarding the rotation cost, we did not find any either. In fact, unexpectedly, children were significantly more accurate on plane-rotation trials than on identical trials[23], $F(1, 9) = 8.17$, $p = .019$ (RTs, $F < 1$). Such result may be due to extraneous factors or to measurement error enhanced by the small size of our sample, especially because in the orientation-based task children did show sensitivity to plane-rotation contrasts: they were as able and as fast on responding different for plane-rotation trials as for fully-different trials, both Fs < 1. In line with prior findings (e.g., Fernandes et al., 2016), and our results on geometric shapes, children showed a mirror performance drop, as they were significantly less accurate on mirror-image than on fully-different trials, $F(1, 9) = 16.94$, $p = .003$ (RTs, $F < 1$).

3.2. Training

We first present the mixed analyses conducted on the performance index described in Chapter 2, and then the analysis on the seven errors types predefined during game development, focusing on the five error types common to both games.

3.2.1. Performance analysis

To explore how performance evolved along training, we adopted the performance index, P[24], proposed in the Method (Chapter 2), and considered four *training periods*, each referring to 10 consecutive challenges: *T1* (first to tenth challenge); *T2* (eleventh to twentieth challenge); *T3* (twenty-first to thirtieth challenge); and *T4* (thirty-first to fortieth challenge). Recall that P accounts for how well children performed the tracing/moving tasks as it considers the number of letter views, the number of errors made in those tasks, and the total

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[23] For $N = 14$ accuracy and RTs did not significantly differ between these trials, both Fs < 1.

[24] $P = NTm\left(1 - \frac{NEm}{NVm}\right)$ NTm: number of tasks successfully completed; NEm: number of errors made; NVm: number of letter views.

of tasks successfully completed (of a total of 204 to 240, as due to technical problems data from 5.80% of the tasks were lost). To assess training efficacy, we thus run a mixed ANOVA on P, with game, training-period (T1; T2; T3; T4) and letter-type (non-reversible; reversible; symmetrical) as factors.

Not surprisingly, the main effect of game was significant, $F(1, 9) = 13.24$, $p = .005$. Children who played the contact game had better performance than those in the draw game, given that the contact game was easier than the draw game, as referred in Chapter 1. The main effect of training period was also significant, $F(3, 27) = 8.68$, $p < .001$, showing an increase in performance along training. The interaction between training period and game was not significant, $F < 1$, suggesting that the two groups of children presented similar rates of learning. There was a significant improvement from the first training period, T1, to the last, T4, $F(1, 9) =21.84$, $p = .001$, and children improved significantly from T1 to T2, $F(1, 9) = 7.14$, $p = .026$, close to significance from T2 to T3, $F(1, 9) = 4.44$, $p = .064$, but from T3 to T4 the improvement was no longer reliable, $F < 1$.

No significant effects of letter type, $F < 1$, or of the interaction between game and letter-type, $F(2, 18) = 2.03$, $p = .161$, were found. Nonetheless, and importantly, the interaction between letter-type and training period was significant, $F(6, 54) = 2.29$, $p = .049$, which tended to be modulated by game: Game x Letter type x Training period, $F(6, 54) = 2.08$, $p = .071$. Given our a priori prediction for performance modulation by letter type and game, we next examined the effect of game on each letter type, separately by training period.

As expected, in the first training period, T1, performance was not modulated by letter-type, $F < 1$, nor by letter-type and game, $F(2, 18) = 2.19$, $p = .141$, as children had just started the training. Given that, as aforementioned, the contact game was the easiest of the two games the main effect of game was significant from the start, $F(1, 9) = 26.47$, $p < .001$.Importantly, already at T2, the interaction between game and letter-type was significant, $F(2, 18) = 6.60$, *p*

= .007, because, as we predicted, children playing the draw game had significantly improved from T1 to T2 specifically for reversible letters, for which orientation is a critical dimension, $F(1, 9) = 22.03$, $p = .001$, but not for non-reversible letters, $F < 1$, or symmetrical letters $F(1, 9) = 2.67$, $p = .137$. As illustrated in Fig. 6, this impact was specific to the draw game, as from T1 to T2 children in the control, contact game did not show any significant improvement in performance for reversible letters, $F < 1$, for non-reversible letters, $F(1, 9) = 2.79$, $p = .129$, or symmetrical letters, $F < 1$. In other words, during T2, i.e., between the 11th and 20th session of training, children playing the draw game already showed a specific advantage for reversible letters which did not held true for the other letter types, and neither occurred for children playing the control, contact game.

Between T2 and T3, children in the draw game maintained their performance for reversible letters, $F < 1$, and now a significant improvement was found for non-reversible letters, $F(1, 9) = 6.47$, $p = .031$ (for symmetrical letters, $F < 1$). In contrast, children playing the contact game continued to present a steady performance for reversible, $F(1, 9) = 1.51$, $p = .250$, and non-reversible letters, $F(1, 9) = 2.76$, $p = .131$, but showed a significant improvement for symmetrical letters, $F(1, 9) = 7.19$, $p = .025$. Between T3 and T4, no significant improvement was found on any letter-type for any of the two groups, all Fs < 2.50, all ps > .150.

When examining the evolution of children´s performance from the beginning to the end of training (i.e., T1 vs T4), children playing the draw game significantly improved for the three letter-types: symmetrical, $F(1, 9) = 8.95$, $p = .015$; non-reversible, $F(1, 9) = 15.69$, $p = .003$; reversible, $F(1, 9) = 14.80$, $p = .004$. Those playing the control, contact game did not show any significant improvement on reversible letters, $F(1, 9) = 1.20$, $p = .301$, as shown in Fig. 6. However, they did show a significant improvement for non-reversible letters, $F(1, 9) = 11.25$, $p = .008$, and tended to improve for symmetrical letters, $F(1, 9) = 4.15$, $p = .072$.

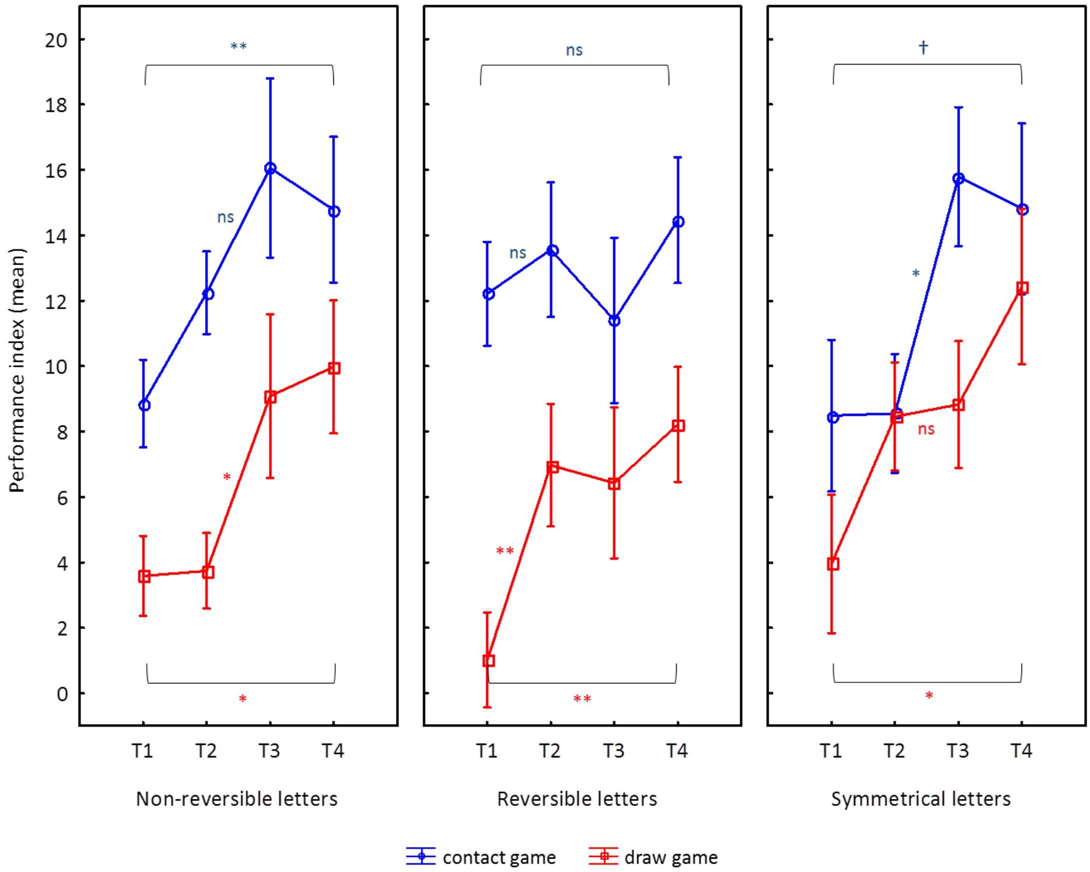

Figure 6 Mean performance index separately by game, letter-type, and training period (T1 to T4). † $p < .10$; * $p < .05$; ** $p < .01$. Vertical bars denote +/- standard error of the mean.

3.2.2. Error analysis

We next examined the errors done while playing the games. Overall, in line with the previous analyses, children who played the draw game presented significantly more errors ($M = 121.83$, $SD = 20.57$) than children in the contact game ($M = 61.00$, $SD = 20.36$), $t(9) = -4.91$, $p < .001$, because the former was harder, as it required more complex motor actions than those necessary for successful performance in the contact game.

In what regards the seven types of errors predefined during game development, we focused on the five error types which occurred in both games: no-start, wrong-start, raising-finger, going-back, and going-out. Note that the two other error types, i.e., wrong-way (going in the wrong way inside the letter) and no-next (not starting the next letter stroke in 6 s), were specific to the draw game[25] (see Chapter 2, for details). This analysis was done separately for each group given that the two games were not directly comparable as they differed on constraints and paths (see Chapter 2).

As shown in Table 10, the most frequent error found for children who played the draw game was of raising-finger type, relative to the wrong-start type errors ($t(10) = 2.45$, $p = .034$), and any other errors (all $t(10)$s > 7.00, all ps < .001). Furthermore, wrong-start error type also occurred more frequently than the other errors (except for raising-finger; comparisons with wrong-start error type, all $t(10)$s > 3.00, ps < .010). Children who played the contact game also did more errors of raising-finger type than of no-start and going-back types ($t(8) = 3.45$, $p < .009$, and $t(8) = 2.93$, $p < .019$, respectively). Errors of raising-finger type did not significantly differed from those of wrong-start or going-out types (both $t(8)$s < 1.50, ps > .180). Errors corresponding to difficulties in not raising the finger before completing letter tracing/moving and in starting the tasks at the right point might be consequence of children have not understood the tasks, not being used to play on tablets (as some children reported), or both.

Table 10 Mean, minimum, and maximum number of errors made in the games, and standard deviation, by error type and by game.

	draw game (N = 6)				**contact game (N = 5)**			
Error type	***Mean***	***Min***	***Max***	***SD***	***Mean***	***Min***	***Max***	***SD***
no-start	5.17	1.00	14.00	4.62	5.00	3.00	9.00	2.55
wrong-start	33.67	27.00	56.00	11.08	13.00	6.00	20.00	5.83
raising-finger	47.50	32.00	56.00	8.24	20.20	7.00	30.00	9.52
going-back	17.50	12.00	28.00	5.92	6.40	2.00	14.00	4.51
going-out	14.17	5.00	20.00	5.49	16.40	6.00	54.00	21.04
wrong-way	1.50	0	3.00	1.22				
no-next	2.33	1.00	5.00	1.51				

[25] Please note that only five out of the seven types of error could occur in the contact game, whereas all seven types could occur in the draw game. Consequently, the probability of occurrence of errors for each error type is not the same for the two games, and hence ANOVAs could not be conducted to compare these data.

3.3. Pre-training vs. Post-training

To examine transfer effects, we finally compared the results on each independent task before and after the training with mixed ANOVAs run on accuracy and on RTs with the factors used in pre-training analyses and the additional within-participants factor testing-phase (pre-training; post-training).

3.3.1. Letter Knowledge

Children's letter knowledge (across games) in each task, and separately by case, is reported in Fig. 7. The main effect of game was not significant, $F(1, 9) = 2.02$, $p = .189$ and did not significantly interact with testing-phase, $F < 1$. Yet, there was a significant main effect of testing-phase, $F(1, 9) = 5.67$, $p = .041$, because, regardless of game, children significantly improved on letter knowledge from pre-training to post-training. We cannot exclude the likely possibility that this result is extraneous to training, given that children continued to do activities with letters at school (and at home) along this period. No interactions with game, with testing-phase, or with the two factors were significant: Game x Testing-phase x Case, $F(1, 9) = 1.16$, $p = .309$, Testing-phase x Task x Case, $F(1, 9) = 4.36$, $p = .066$, Game x Task, Game x Task x Case, Testing-phase x Task, Testing-phase x Game x Task, and the four-way interaction between all factors, all *F*s < 1,

The main effect of case was significant, $F(1, 9) = 35.01$, $p < .001$, as it was already in the pre-training phase, and it was not modulated by testing-phase, $F < 1$, nor by game, $F(1, 9) = 3.06$, $p = .114$. Overall, children knew more upper-case than lower-case letters. No other significant effects or interactions were found: Task, $F < 1$, Task x Case, $F(1, 9) = 1.19$, $p = .304$.

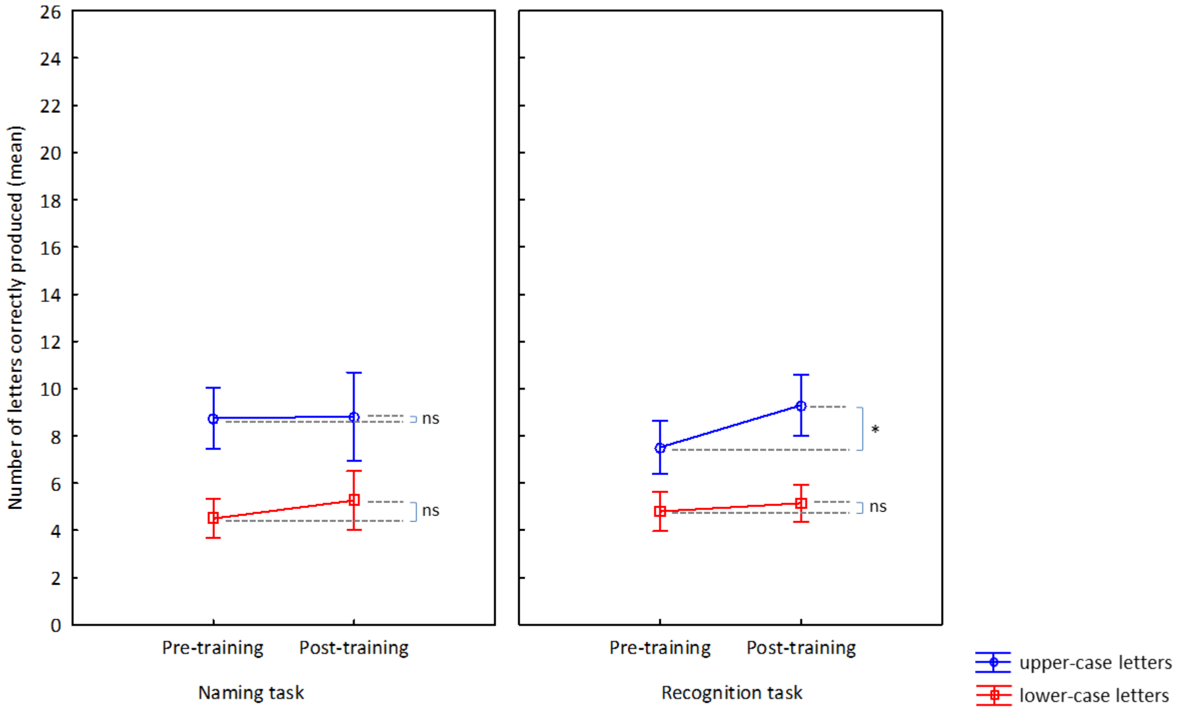

Figure 7 Mean number of letters correctly named (on the left graph) and recognised (on the right) out of 26, across games, separately by case, and testing phase.
ns – non-significant; * $p < .05$. Vertical bars denote +/- standard error of the mean.

3.3.2. Four-alternative forced-choice task

The main effects of testing-phase and game were not significant, both *F*s < 1, and neither was their interaction, $F(1, 9) = 1.98$, $p = .193$. No other interactions with game, testing-phase, or both factors were significant (Testing-phase x Letter-set x Letter-type, $F(2, 18) = 1.31$, $p = .294$; all other *F*s < 1). Contrary to our prediction, no significant differences were found between pre- and post-training on this task for children trained in any of the two games although they still had room for improvement. As aforementioned, performance was not at ceiling in the pre-training phase.

The only significant main effect found was that of letter-type, $F(2, 18) = 51.84$, $p < .001$ (Letter-set, $F < 1$), with a pattern of results similar to the one at pre-training: children had better performance for symmetrical than asymmetrical letters (symmetrical vs. non-reversible, $F(1, 9) = 75.45$, $p < .001$; symmetrical vs. reversible, $F(1, 9) = 99.54$, $p < .001$), and performance for the two asymmetrical letter types did not significantly differ from each other, *F*(1, 9) = 1.35, *p* = .274. No significant interaction between letter-set and letter-type was found, *F*(2, 18) = 3.02, *p* = .074.

We then examined possible effects of training regarding the presence of the orientation-distractor in trials with asymmetrical letters. Similarly to what was found at pre-training, all children had worse performance when a mirror-image rather than a plane-rotation was the orientation distractor presented, *F*(1, 9) = 11.96, *p* = .007, (Orientation distractor x Testing-phase, and Orientation distractor x Game, both *F*s < 1).

Given that we expected that training in the draw game, in comparison with that in the control game, would lead to a stronger improvement in trials with a mirror-image distractor (see Chapter 1), we explored the interaction between testing-phase, game, letter-set, and orientation-distractor, *F*(1, 9) = 3.71, *p* = .086 by trial type. No significant interaction between testing-phase, game, and letter-set was found neither for trials with a mirror-image distractor, *F*(1, 9) = 2.24, *p* = .169 or with a plane-rotation distractor, *F*(1, 9) = 1.14, *p* = .314).

No other interactions with orientation distractor were significant (Orientation-distractor x Letter-set, *F*(1, 9) = 3.82, *p* = .082; Orientation-distractor x Letter-set x Letter-type, *F*(1, 9) = 2.39, *p* = .156; all other interactions, *F* < 1).

The interaction between letter-set and letter type was marginally significant, *F*(2, 18) = 4.89, *p* = .054. This interaction was marginally modulated by testing phase , *F*(1, 9) = 4.77, *p* = .057. At pre-training letter-set did not modulate letter-type, *F*(1, 9) = 1.05, p = .332, but at post-training letter-type was significantly modulated by letter-set, *F*(1, 9) = 11.21, *p* = .009: for trained letters children were significantly less accurate for reversible letters than for non-reversible letters, *F*(1, 9) = 7.15, *p* = .025, whereas for untrained letters no significant differences were found between the two letters types, *F*(1, 9) = 2.57, *p* = .143. Nevertheless, accuracy on reversible letters when compared with non-reversible letters did not significantly change from pre-training to post-training neither for trained letters, *F*(1, 9) = 1.23, *p* = .295

nor for untrained letters, $F(1, 9) = 1.39$, $p = .268$. In other words, although after training children became sensitive to letter-type, we must be careful in saying that training has significantly impacted children's sensitivity to letter type, as no significant differences were found between the results at pre-training and those at post-training.

3.3.3. Same-different tasks

We next explored the impact of training on the results of the same-different tasks for each of the two visual categories.

3.3.3.1. Geometric shapes

The main effect of game was not significant, either on accuracy or RTs, both *F*s < 1, but the main effect of testing-phase was significant on accuracy, $F(1, 9) = 17.98$, $p = .002$, and RTs, $F(1, 9) = 58.33$, $p < .001$. Children had a global improvement on performance from pre- to post-training. This held true for both games, as the main effect of testing-phase was not modulated by game on either accuracy, $F(1, 9) = 3.22$, $p = .106$, or RTs, $F(1, 9) = 2.90$, $p = .123$. This improvement can be due to training in the games or to a test-retest effect.

As reported for the pre-training phase the main effect of trial was significant on accuracy, $F(3, 27) = 6.14$, $p = .003$, and also on RTs, $F(3, 27) = 4.22$, $p = .014$. The only significant interaction found was between testing-phase, task, and trial on RTs, $F(3, 27) = 3.07$, $p = .045$ (accuracy, $F < 1$; note that the four-way interaction between all factors at test, i.e., Testing-phase x Task x Trial x Game, was not significant on accuracy or RTs, *F*s < 1; see Table 11 for the statistical results for the remaining interactions). We decomposed this three-way interaction and examined each task separately, only for RTs, considering an index of orientation discrimination in each task.

In the shape-based task we compared mirror-image, and plane rotation trials, with identical trials, measuring these two orientation costs in performance due to automatic orientation processing. We thus checked whether the orientation costs were modulated by testing-phase and no significant differences were found for mirror cost on RTs ($F < 1$; accuracy, $F < 1$) from the pre-training phase to the post-training phase. On the contrary, the rotation cost significantly increased from pre- to post-training, $F(1, 9) = 7.19$, $p = 0.025$ (accuracy, $F < 1$) as children at post-training were even slower in plane-rotation trials relative to fully-different trials than at pre-training.

In the orientation-based task we used the performance drop index, which examined children's explicit ability to discriminate the orientation contrasts by comparing the performance in mirror-image, and plane-rotation trials, relative to fully-different trials. The comparison between testing-phases showed that from pre- to post-training the mirror performance drop (RTs, F (3, 27) = 3.91, p = .080, accuracy, $F < 1$), and the rotation performance drop (RTs and accuracy, both Fs < 1) did not significantly change.

Table 11 *F* and *p* values for same-different tasks with geometric shapes (considering pre- and post-training results) regarding non-significant interactions, on accuracy and RTs, not presented in the text (*df* - degrees of freedom).

Interaction	**Outcome**	***df***	***F***	***p***
Game x Task	accuracy RT	1, 9	<1 2.60	 .141
Testing-phase x Task	accuracy RT	1, 9	< 1	
Testing-phase x Game x Task	accuracy RT	1, 9	< 1	
Game x Trial	accuracy RT	3, 27	1.84 < 1	.164
Testing-phase x Trial	accuracy RT	3, 27	< 1 1.48	 .244
Testing-phase x Game x Trial	accuracy RT	3, 27	< 1	
Task x Trial	accuracy RT	3,27	2.09 2.31	.126 .098
Game x Task x Trial	accuracy RT	3, 27	< 1 1.69	 .340
Testing-phase x Game x Task x Trial	accuracy RT	3, 27	< 1	

Across testing-phases children were overall slower on shape-based than on orientation-based judgments of geometric shapes (main effect of task, RTs, F (1, 9) = 10.84, p = .009; accuracy, F < 1).

3.3.3.2. Letters

The main effect of testing-phase was significant on accuracy, F(1, 9) = 19.54, p = .002, as for geometric shapes, but not on RTs, F(1, 9) = 4.48, p = .063), but did not interact with game (accuracy and RTs, both Fs < 1). All children were significantly more accurate at post-training than at pre-training, which did not significantly changed with trial (on accuracy Testing-phase x Trial was not significant, F(3, 27) = 1.74, p = .182; on RTs, F(3, 27) = 2.60, p = .073). Again, this improvement might be due to test-retest effects. Other interactions with testing-phase and all interactions with testing phase and game were non-significant, as shown in Table 12.

The main effect of task was significant on RTs, F(1, 9) = 7.33, p = .024 (accuracy: F < 1), with children being significantly slower in the shape-based than in the orientation-based, and it was modulated by game on RTs F(1, 9) = 6.79, p = .028 (accuracy, F < 1): children in the contact game were slower in the shape-based task than in the orientation-based task (F(1, 9) = 12.94, p = .006), whereas children in the draw game had similar RTs in the two tasks (F < 1), but no significant differences were found between the two games in the shape-based task or in the orientation-based task (both Fs < 1).

The interaction between task and letter-type was significant on accuracy, F(1, 9) = 9.43, p = .013 (RTs, F < 1), contrary to what was found in the pre-training phase, and it was not modulated by game (accuracy, F < 1, RTs, F(1, 9) = 1.63, p = .233). Across training-phases, in the shape-based task, no significant differences were found between the two letter-types neither on accuracy, F(1, 9) = 3.61, p = .090, nor RTs, F < 1; in the orientation-based task, children were significantly less accurate on reversible letters than on non-reversible letters, F (1, 9) = 6.53, p = .031, but RTs did not significantly differ between the two letter-types, $F < 1$. Given that the interaction between task, letter-type, and testing-phase, and the four-way interaction between task, letter-type, testing-phase, and game, were not significant (as aforementioned), and this result is probably due to the small size of the sample, we will not discuss it further.

As at pre-training, the main effect of trial was not significant on accuracy, $F(3, 27) = 2.62$, $p = .071$, or on RTs, $F < 1$, and it was not modulated by game, neither on accuracy, $F(3, 27) = 1.60$, $p = .212$, nor on RTs, $F < 1$. The interaction between task and trial (that at pre-training was marginally significant on accuracy) was not significant on accuracy, $F(3, 27) = 2.43$, $p = .087$ or RTs, $F < 1$, and the three way interaction between game, task and trial was not significant on accuracy, $F < 1$, or RTs, $F(3, 27) = 2.60$, $p = .073$. No other significant main effects were found neither on accuracy nor RTs (Game, and Letter-type: both Fs < 1) and, as shown in Table 12, all other interactions were non-significant.

Table 12 *F* and *p* values for same-different tasks with letters (considering pre- and post-training results) regarding non-significant interactions, on accuracy and RTs, not presented in the text (*df* - degrees of freedom).

Interaction	Outcome	*df*	*F*	*p*
Testing-phase x Task	accuracy RT	1, 9	< 1	
Testing-phase Game x Task	accuracy RT	1, 9	<1	
Testing-phase x Letter-type	accuracy RT	1, 9	< 1	
Testing-phase x Game x Letter type	accuracy RT	1, 9	< 1 2.66	 .137
Testing-phase x Game x Trial	accuracy RT	3, 27	2.17 < 1	.115
Testing-phase x Task x Letter-type	accuracy RT	1, 9	< 1	
Testing-phase x Game x Task x Letter-type	accuracy RT	1, 9	1.02 2.75	.340 .132
Testing-phase x Task x Trial	accuracy RT	3, 27	1.07 < 1	.378
Testing-phase x Game x Task x Trial	accuracy RT	3, 27	< 1	
Testing-phase x Letter-type x Trial	accuracy RT	3, 27	2.40 1.31	.090 .292
Testing-phase x Task x Letter-type x Trial	accuracy RT	3, 27	2.59 < 1	.074
Testing-phase x Game x Letter-type x Trial	accuracy RT	3, 27	1.77 < 1	.177
Testing-phase x Game x Task x Letter-type x Trial	accuracy RT	3, 27	< 1 1.21	 .326
Letter-type x Game	accuracy RT	1, 9	< 1	
Letter-type x Trial	accuracy RT	3, 27	< 1	
Letter-type x Trial x Game	accuracy RT	3, 27	1.21 < 1	.325
Task x Letter-type x Trial	accuracy RT	3, 27	< 1 1.48	 .242
Task x Letter-type x Trial x Game	accuracy RT	3, 27	< 1	

4. Discussion

The purpose of this study was to explore how motor training on the specific visuomotor representations of letters (presumably supported by the operation of the visual dorsal stream) contributes to orientation processing during visual recognition of mirror images (which relies on the operation of the ventral visual stream). Based on prior literature from neuroscience and cognitive psychology, and supported by computer science following the human-computer interaction principles (Nielsen, 1993) to design the two training games that were specifically developed for this study, we devised a longitudinal training study on which 11 preliterate children trained motor actions with letters by playing one of two games. Children were also tested in independent tasks before and after the training in order to explore transfer effects of learning outside the training.

The two motor training games differed only on the type of motor tasks performed by children on letters: in the critical, draw game, children traced and copied letters, whereas in the control, contact game children moved letters on defined paths or freely. The same six letters (i.e., o, x, d, p, e, k) were used in both games. Reversible and non-reversible letters were used to explore the impact of motor training on mirror-image discrimination of letters for which orientation is the only diagnostic feature. Children were not told the name of the letters during training because that could assist on letter recognition (Treiman & Kessler, 2003), and letters were presented out of any context (e.g., a story), as it could contribute to letter recognition and discrimination performance due to motivational aspects or other (Simons et al., 2016).

The training results showed that motor representations of letters emerge during motor experience that is congruent with the shape of the letter. This specific motor experience was more important for letters for which orientation is the only distinctive feature, that is, the reversible letters than for letters that may be merely discriminated by shape.

In the draw game, children trained motor actions by tracing and copying of letters and had significantly improved their performance for all letter types from the beginning to the end of the training. Based on the account of Goodale and Humphrey (1998) regarding the interaction between the two visual streams during goal-directed actions, we may say that during the execution of tracing tasks visual information was processed by the ventral visual stream to create an internal representation of the scene that included accurate information about the goals of the motor actions (e.g., the position in the scene of the task-marker to be pressed); this information assisted the operation of the dorsal visual stream that transformed it as required for motor planning and motor execution, activating pre-motor areas. With motor practice in the tracing tasks, letter motor programs emerged and assisted on subsequent execution of the goal directed actions in those tasks, which led to the improvement found, in agreement with prior studies that show that letter perception activates motor brain areas (James & Gauthier, 2006), as well as the adequate motor program at Exner area to write the letter (Nakamura et al., 2012).

Our study adds to prior findings that handwriting practice can assist mirror-image discrimination (James, 2010; Longcamp et al., 2005) by showing that motor representations of letters are more important for reversible letters than for letters that can be discriminated by shape, either non-reversible or symmetrical. Indeed, in the draw game children improved significantly first, for reversible letters, from T1 to T2, only next, from T2 to T3, for non-reversible letters, and finally, for symmetrical letters, for which the improvement followed a linear trend from T1 and T4. Such pattern of results is not trivial, as at T1 performance on each game was similar for all letter types. Given that children in our study had difficulties in processing mirror images, in line with prior studies with pre-readers (Casey, 1986; Gibson et al., 1962; Fernandes et al., 2016), and following the mirror invariance of the ventral visual stream (Logothetis et al., 1995; Rollenhagen & Olson, 2000), it does seem that it was the operation of the dorsal visual stream, which is sensitive to mirror-image differences (Rice et al., 2007; Valyear et al, 2006) that has assisted children on the significant improvement found for reversible letters. In the same vein, motor experience was less important for executing tracing tasks on letters for which perceptual experience may suffice for letter discrimination. In fact, regular exposure to printing may be enough to acquire sensitivity to the regular orientation of asymmetrical non-reversible letters (Pegado, Nakamura & Hannagan, 2014) due to visual statistical learning (Treiman & Kessler, 2011). In what concerns symmetrical letters, the visual system is very effective and rapid in detecting symmetry (Wagemans, 1997), and orientation processing is not necessary to discriminate them (Treiman & Kessler, 2011).

The results in the contact game agree with the findings in the draw game by showing that when motor experience is not congruent with letter shape, letter motor representations do not emerge to assist children in goal-directed actions on the letters that are the most difficult to discriminate. Indeed, for these reversible letters no significant improvement was found along training in the contact game. For non-reversible letters there was a significant improvement in the contact game, following a linear trend from T1 to T4. For symmetrical letters children tended to improve from T1 to T4 showing a significant improvement from T2 to T3. This pattern of results is consistent with motor representations being crucial to assist recognition of letters that cannot be discriminated by shape, as we predicted.

As a further matter, important especially in what concerns training studies with preliterate children, this study showed that games developed in accordance to principles of human-computer interaction may be an effective training tool in research, useful in keeping preliterate children motivated to train on a daily basis, during long periods of time.

The independent tasks used to assess transfer informed us about children's abilities in orientation processing before and after training. Children performed a 4AFC task with letters to assess letter recognition and mirror-image discrimination. Two same-different tasks were performed with letters, and two with geometric shapes. The latter material was novel to all children and was used to verify about transfer effects to discrimination tasks of non-linguistic stimuli. For each material children were assessed on explicit orientation processing in orientation-based tasks, and on automatic orientation processing in shape-based tasks, that informed about sensitivity to mirror-image and plane rotation contrasts.

Before training, the two groups of children did not significantly differ in their performance in ancillary measures or in all measures in the independent tasks, thus ensuring they were matched in cognitive abilities, letter knowledge, and orientation processing abilities. All children showed difficulty in mirror-image discrimination in line with prior findings (Fernandes et al., 2016). Children were sensitive to plane-rotation orientation contrasts in agreement with the sensitivity of the occipitotemporal cortex to plane-rotation contrasts (Hoffman & Logothetis, 2009; Logothetis et al., 1995; Rollenhagen & Olson, 2000) and corroborating that preliterate children do not have a prevalent problem with orientation processing (Fernandes et al., 2016).

The results on the 4AFC task before training, and across training phases, showed that children had difficulty in mirror-image discrimination. Children were significantly less accurate on trials with a mirror-image distractor than with a plane-rotation distractor, agreeing with prior results (Fernandes et al., 2016). To the best of our knowledge, these results are original, as no other study has hitherto shown differences in orientation processing for mirror and plane-rotation contrasts in a 4AFC task. This is an important result, not only given the replication crisis currently discussed (e.g., Lilienfeld, 2017; Pashler & Harris, 2012), but also because finding such pattern with a task with less working-memory demands than same-different tasks measuring explicit orientation processing gives credence to the suggestion that mirror-image and plane-rotation contrasts are processed by (at least partially) independent mechanisms (Turnbull & McCarthy, 1996). Therefore, our results provide an original contribution showing that the difficulty pre-literate children have in orientation processing of mirror images of letters is not merely due to working-memory demands of the conventional same-different tasks (e.g., Casey, 1986; Gibson et al., 1962; Fernandes et al., 2016; Kolinsky et al., 2011).

In the same-different tasks all children were significantly more accurate after the training than before, being faster for geometric shapes and tending to be faster for the tasks with letters regardless of task. This improvement could be due to additional visual exposure to letters in the games. However, familiarity with the material cannot explain the overall improvement found in the tasks with geometric shapes, as children did not train with this material. Another explanation could be that such improvement was due to training, i.e., to motor experience with letters in the games that recruited the dorsal visual stream. As a consequence, in the same way that the dorsal visual stream and motor information assist non-literate (adults and children) in orientation processing in vision-to-perception tasks (Fernandes et al., 2017), in the present case motor information (i.e., letter motor representation in the draw game; in the contact game information regarding, e.g., the position in the letter where children should press it) may have promoted children's sensitivity to orientation. The improvement in discrimination of letters in the same-different tasks would have spread to geometric shapes because neurons at the ventral visual system, in the VWFA, are particularly tuned to process shapes with features similar to those of letters (Fernandes et al., 2016; Hannagan, Amedi, Cohen, Dehaene-Lambertz, & Dehaene, 2015). If motor experience with letters was responsible for the significant improvement found for the same-different tasks, we would expect to find a significant improvement in performance for the 4AFC task as well, which was not the case. Another possible reason for the significant gain in performance found in the same-different tasks may be the increased familiarity with testing procedures at post-training, not with the materials. At post-training children were already familiar with which keyboard key corresponded to each answer (see Chapter 2) thus significantly improving accuracy and being faster in answering. Such explanation has the advantage over the former that it may agree with the absence of significant differences between pre-and post-training in the 4AFC task: in this task there was no room for improvement due to familiarity with testing procedures because children did not interact with the computer keyboard. In sum, the significant improvement found in the same-different tasks after the training was most likely due to increased familiarity with testing procedures at the post-training phase.

At post-training, in the same-different shape-based task with geometric shapes, all children were even slower (but not less accurate) in answering same in plane-rotation trials when compared with identical trials, than at pre-training. This increase in the rotation cost for geometric shapes, may be due to training of a plane-rotation contrast in the draw game (i.e., d-p), or in the contact game being visually exposed and having motor contact with that contrast. Given that the ventral visual stream is originally sensitive to plane-rotation contrasts, (e.g., Logothetis et al., 1995) training would have contributed to increase children's sensitivity to this orientation contrast. If this was the case, we would expect, first, to find the same training effect on automatic orientation processing of plane-rotation pairs of letters. Actually, because before training children were unexpectedly significantly more accurate on plane-rotation trials than on the easiest trials in the shape-based task, i.e., identical trials, but that was no longer true after the training, it is possible that training had an effect on automatic orientation processing of plane-rotation contrasts of letters. Second, we would expect to find an impact in the orientation-based tasks, showed by a significantly smaller performance drop at post- than at pre-training. Such significant decrease was not found, probably because already at pre-training children did not present a significant rotation performance drop neither for letters nor for geometric shapes. In other words, these results suggest that motor experience with letters that differ by an orientation contrast may lead to the involvement of the dorsal visual stream in the discrimination of pairs of letters differing by the trained contrast, with the result that sensitivity to that orientation contrast increases for letters, and even for geometric shapes due to a spillover effect. Nevertheless, we cannot exclude that experience in the pre-training testing phase in explicit discrimination (in the orientation-based tasks) of orientation contrasts to which children were already sensitive, i.e., the plane-rotation contrast, has led to increased sensitivity to that contrast at post-training, but not to increased sensitivity to contrasts to which children were not sensitive at pre-training, i.e., mirror-image contrasts. To positively disentangle training effects and test-retest effects future research should include a third group of children that would perform the experimental tasks in the two testing phases and would not play any letter game during the training period, only ludic games (to ensure that motivational aspects would not influence the post-training results; see Simon et al., 2016).

When we explored transfer effects to the independent tasks by comparing pre- and post-training results in the 4AFC and same-different tasks, against our predictions and despite the evidence found suggesting that letter motor representations have emerged during training in the draw game, we did not find significant differences between the two games. As non-significant results prevent the rejection of the null hypothesis (e.g., Dienes, 2011), the results in the present study did not provide statistically significant evidence, nor refuted, that letter motor representations assist in mirror-image discrimination in independent, not related with training, vision-for-perception tasks. At this point, it is important to remark that the use of conventional statistics methods that rely on significance testing of the null hypothesis may be regarded as limitation of the present study. Instead, the use of the Bayesian approach to hypotheses testing (which by comparing two theories, e.g., the research hypothesis and the null hypothesis, calculates the *likelihood* of one theory compared to the other) would have allowed us to derive meaning from our data (Dienes, 2011, 2014). In other words, whereas in conventional statistics the aim is to reject the null hypothesis and the only conclusive result possible is its rejection thru significant results, with the Bayesian approach the research hypothesis is tested against the null hypothesis, and so a null result can provide evidence that the research hypothesis was not supported against the null hypothesis, i.e., we could have reached a conclusion.

The non-significant results found may be due to the small size of the sample. Although we initially planned to have 20 participants on each group (based on previous studies with pre-literate children; Fernandes et al., 2016, 2017) due to the time available to perform the study only 17 children were tested, and due to sample attrition, an inexorable fact in longitudinal studies (Grammer, Coffman, Ornstein, and Morrison, 2013), only 11 children (5 in the draw group, 6 in the control, contact group) completed all phases of the study. Such small sample lacked statistical power, and so it can be expected that it delivers results with greater variability than a larger sample, thus leading to results that did not support our predictions and were even inconclusive (Bertamini & Munafò, 2012). Corroborating this view, studies showing a significant increase in performance as result of handwriting training, had at least 12 participants per group (e.g., Li & James, 2016; Longcamp et al., 2005), in contrast with studies with smaller samples that failed to get behavioural significant results due to motor training, (e.g., James, 2010).

Another aspect that may have contributed to the non-significant results found is the poor letter knowledge of children in the present study (who could, on average, name less than 7 letters of the alphabet before the training, and less than 8 letters after the training), given that children who know more letters seem to be more efficient in processing single letters (Evans, Saint-Aubin & Landry, 2009), and prior studies have shown the importance of letter knowledge for letter discrimination (Li & James, 2016; Fernandes et al., 2016). In the 4AFC task children still had room to improve their accuracy after the training as they did not perform at ceiling at pre-training. However, no significant improvement was found, opposite to a recent study from Li & James (2016). In this study, in a similar 4AFC task, pre-literate children improved their accuracy in symbol recognition regardless of type of training (visuomotor or visual only); importantly, they all could name at least 75% of the letters of the alphabet. Corroborating that the poor letter knowledge of children in the present study may have contributed to the null results found is the fact that in the same different-tasks children did not show any significant differences in mirror-image orientation processing abilities that prior studies showed to be positively correlated with letter knowledge (Fernandes et al., 2016). It is thus possible that only if children are able to name the letters with which they train, the operation of the dorsal visual stream may assist the discrimination of an orientation contrast that was not trained. Then, children would be able to use the letter names as a unique identifier for the trained letters (Share, 2004). Therefore, if during demonstrations and tracing/moving tasks in the games the letter names were presented, we could expect that children in both games improved mirror-image processing, with children trained in the draw game showing even better mirror-image processing abilities than those in the contact game due to assistance of letter motor representations.

Although it seems that motor training in the two games had an impact in plane-rotations processing in the same-different tasks, for the sake of this discussion we may argue that the null results found could demonstrate that no transfer occurred from training to testing tasks. Transfer is usually observed when training and testing contexts and tasks are similar (Barnett & Ceci, 2002; see also Simons et al., 2016). In the present study, the training context was ludic being probably more motivational than the experimental context, and the tasks, and the skills necessary to perform them, were different: in the training context children performed visuomotor tasks, training visuomotor skills, whereas in the testing context children performed visual tasks which strongly demanded perceptual discrimination skills.

Thus, transfer may have not occured because the two contexts shared very few elements. We may also consider the neuroanatomical account of transfer proposed by Atherton (2007), which suggests that transfer will more probably occur if the brain regions that underpin the training and testing tasks are co-activated and interconnected. It may then be the case that in the present study interconnections between areas supporting the training and testing tasks started developing after motor training (in the game draw or in both games), but as they were still emerging no transfer effects were observed in the testing tasks. Exploring which brain regions are co-activated and interconnected during motor training on letters and visual perception of letters, would contribute to understand which neural mechanisms must be in place so that training on letter motor representations assists on mirror-image discrimination more than other type of training.

Future directions of our study could involve refinement of the draw game, by exploring the use of an intelligent artificial agent to analyse children's letter productions in copy tasks, give feedback, and adjust task demands and controls according to children's performance, based on letter visual features and motor parameters that are relevant to writing fluency (e.g., letter size, tracing time, velocity, velocity peaks, number of stops or lifts of the finger/pen during stroke's writing; pressure on the tablet; Jolly & Gentaz, 2013). Importantly, feedback should focus on letter visual features as familiarity with these contributes to learning of letters (Fernandes et al., 2016), and on motor parameters to assist children in writing fluency improvement. Adjustment of task parameters would be done based on children's past performance on each letter. In this way, training would be tailored for each child, according to their performance along time (e.g., above a certain level of expertise in copying a letter, children could be asked to produce it in the absence of the letter template) ensuring a correct balance between children's abilities and task demands, while keeping children motivated and engaged in training (Kiili, 2005; Martinovic et al., 2016; Ryan & Deci, 2000). Moreover, because on-line evaluation of letter productions and feedback would be available, motor training could rely only on motor production of variable instances of a letter, which according to James & Engelhardt (2012) is the only form of motor practice with letters that has impact on letter visual processing.

Literacy keeps spreading worldwide (UNESCO, 2017) but still 61 million children (aged between 6 and 11 years) do not go to school, being at risk of never learning to read and write (UNESCO, 2013). To overcome such devastating state of affairs, UNESCO remarks that the use of technological devices that young people enjoy may promote active engagement with learning and be a valuable classroom and home learning resource (UNESCO, 2013, p. 10). It is thus our conviction that games similar to the draw game, available in mobile devices, and supported by intelligent artificial agents for training customization, may be a valuable learning tool for preliterate children, especially in environments in which shortage of teachers prevents literacy acquisition (UNESCO, 2013).

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Appendices

Appendix I - Game lines

1. Narrator

Game presentation

Olá! Fico muito contente por jogares este jogo! Vamos fazer brincadeiras com as letras. Vamos a isso? Ah, mas primeiro escolhe o teu ajudante.

Instructions for assistant choice

Carrega no ajudante que queres que te ajude no jogo.

2. Assistants

(the numbers on the left of the lines indicate the different alternatives used in the games)

Artur the Magician

Assistant presentation - draw game

Olá! Eu sou o Mágico Artur. Venho do sítio mágico do reino do Arco-íris especialmente para brincar contigo o jogo das letras! Vou pedir-te para fazeres letras e vais ganhar estrelinhas! Que maravilha! E quanto mais estrelinhas ganhares, melhor, vais ver, porque depois vais poder trocar essas estrelinhas por um prémio. E sabes que prémios são esses? São fantásticos! Podes jogar um jogo, podes ouvir uma música, podes cantar uma canção, ou podes ver um filme. Muito divertido! Vamos a isso?

Assistant presentation - contact game

Olá! Eu sou o Mágico Artur. Venho do sítio mágico do reino do Arco-íris especialmente para brincar contigo o jogo das letras! Vou pedir-te para brincares com letras e vais ganhar estrelinhas! Que maravilha! E quanto mais estrelinhas ganhares, melhor, vais ver, porque depois vais poder trocar essas estrelinhas por um prémio. E sabes que prémios são esses? São fantásticos! Podes jogar um jogo, podes ouvir uma música, podes cantar uma canção, ou podes ver um filme. Muito divertido! Vamos a isso?

Two-mission challenge presentation

1 Temos um desafio onde tu tens que realizar duas missões... e eu, vou dar-te a magia dos Mágicos!

2 Temos um desafio e tu tens que realizar duas missões, e eu, vou ajudar-te.

Three-mission challenge presentation

1 Temos um desafio onde tens que realizar três missões, e eu, vou dar-te a magia dos Mágicos!

2 Temos um desafio onde tu tens que realizar três missões, e eu, vou ajudar-te!

First mission presentation

1 Vamos então para a nossa 1ª missão! De cada vez vais brincar com uma letra de uma maneira especial. Primeiro vou mostrar-te como é, e depois fazes tu! Vou ver se tens tanto jeito como eu para esta brincadeira! Que alegria! E eu estou aqui ao teu lado, e vou sempre ajudar-te. Primeiro vamos ver.

2 Vamos então para a nossa 1ª missão de hoje. Já sabes que vais brincar com letras de uma maneira especial. Vou mostrar-te como é, e depois fazes tu! Vou ver se ainda sabes fazer. Vamos lá à nossa brincadeira! Que alegria! E eu estou aqui ao teu lado, e vou sempre ajudar-te, mas primeiro, vamos ver.

Second mission presentation

1 Agora, vamos para a nossa 2ª missão! Mais letrinhas para brincarmos. Que divertido! E eu sempre ao teu lado a ajudar-te! Vamos ver.

2 Olha, agora vamos para a nossa 2ª missão! Mais letrinhas para brincares! Mas já sabes, eu ajudo-te. Vamos ver.

3 Olha, agora vamos para a nossa 2ª missão! Mais letrinhas para brincares! São as letrinhas que temos no sítio mágico do arco-íris e todos brincamos com elas. Vamos ver.

Third mission presentation

Agora vamos para a nossa 3ª missão! Estamos quase, quase no fim [voz lamentosa]. Foi tão divertido... Mas vamos ver.

Demonstration presentation

1 Cá estamos! Vê com muita atenção o que é para fazer, para ficares a saber fazer, tão bem como eu!

2 Cá estamos! Vê com muita atenção como se faz, para ficares a saber fazer tão bem como todos os mágicos!

3 Vê com muita atenção como se faz, para ficares a saber fazer tão bem como todos os mágicos!

4 Vou mostrar-te como é que um verdadeiro mestre da magia faz! Vamos ver.

5 Cá estamos. Vou mostrar-te como é que um verdadeiro mágico faz no sítio mágico do arco-íris.

6 Cá estamos! Vê com muita atenção como é que os mágicos fazem no sítio mágico do arco-íris!

Indication to start tracing/moving scene

1 Agora é tua vez! Faz tu para ganhares uma estrelinha!

2 Vamos, agora faz tu, para ganhares uma estrelinha

3 Queres mais uma estrelinha? Então, faz tu!

4 É a tua vez! Faz como eu te mostrei para ganhares mais uma estrelinha.

Congratulations after successful completion of tracing/moving task

1 Muito bem! Ganhaste uma estrela!

2 Oh que bom! Ganhaste mais uma estrela!

3 Excelente! Ganhaste uma estrela!

4 Iupi! Ganhaste mais uma estrela!

5 Fantástico! Ganhaste uma estrela!

6 Ficou óptimo! Tens mais uma estrela!

Copying task presentation (draw game)

1 E agora, para terminares esta missão, só falta copiares esta letra. Vai ser muito engraçado!
Fazes a cópia onde anda a mãozinha; quando acabares carregas no quadradinho azul. Mas só quando acabares.

2 E agora para terminares esta missão, só tens que copiar esta letra. Mostra-me como fazes!
Fazes a cópia onde anda a mãozinha; quando

Free-moving task presentation (contact game)

Agora, para terminares esta missão, só tens que levar esta letra até ao sítio onde anda a mãozinha. Quando acabares, carregas no quadradinho azul. Mas só quando acabares.
Diverte-te!

acabares carregas no quadradinho azul. Mas só quando acabares.

Copying task presentation end line

1 Estás a postos? Boa cópia!

2 Vamos a isso. Boa cópia!

3 Podes começar. Boa cópia!

4 Vamos lá. Boa cópia.

Acknowledgement for copying task completion	**Acknowledgement for free-moving task completion**
Obrigado! Espero que tenhas feito uma cópia bonita!	Espero que tenhas gostado desta brincadeira!

Congratulations at the end of a challenge (when children won all six stars)

1 Parabéns! Completaste todas as missões e por isso ganhaste todas as estrelas que havia para ganhar! Que bom! Carrega no presente e depois, põe as estrelinhas lá dentro. E vê o que acontece...

2 Parabéns! Completaste todas as missões e no sítio mágico do arco-íris todos os mágicos estão contentes. Carrega no presente e depois, põe as estrelinhas lá dentro. E vê o que acontece...

3 Que maravilha! Completaste todas as missões. Que fantástico!
Carrega no presente e depois, põe as estrelinhas lá dentro. E vê o que acontece...

4 Parabéns! Fizeste tudo bem. No sítio mágico do arco-íris todos os mágicos vão celebrar porque ganhaste todas as estrelas. Carrega no presente e depois, põe as estrelinhas lá dentro. E vê o que acontece...

Instructions to choose and collect the prize when children won all six stars

Agora podes escolher o teu prémio! Se carregares no Mágico Artur, ele deixa-te jogar um jogo. Se carregares na Princesa Filipa, ela toca uma canção. E se carregares no Palhaço Barnabé, ele mostra-te um filme. Podes escolher.

Instructions to collect the prize when children won less than six stars

1 Chegaste ao fim, mas fizeste alguns erros... Que pena. Não tens as estrelinhas todas. Mas podes trocar as tuas estrelinhas por uma canção. Carrega na Princesa Filipa e ouve a canção que ela escolheu para ti.

2 Chegaste ao fim, mas fizeste alguns erros... Que pena. Não tens as estrelinhas todas. Da próxima vez vais ver que corre melhor. No sítio mágico do arco-íris todos os mágicos estarão do teu lado a dar-te força para correr melhor.
Agora, podes ouvir uma canção. Carrega na Princesa Filipa e ouve a canção que ela escolheu para ti.

Goodbye at the end of the game

1 Acabámos por hoje. Tenho de ir fazer magias. Até amanhã.

2 Já acabámos. Agora tenho que ir a correr para a festa dos mágicos do arco-íris. Até amanhã.

3 Vou ter com a princesa Filipa e com o palhaço Barnabé. Até amanhã!

4 Até à próxima! Vou fazer magia com as letras que aprendeste hoje.

Clown Barnabé

Assistant presentation - draw game

Olá! Olá! Eu sou o Palhaço Barnabé.

Venho do Circo do Arco-íris especialmente para brincar contigo o jogo das letras!

Vou pedir-te para fazeres letras e sempre que fizeres vais ganhar estrelinhas! Que maravilha! E quanto mais estrelinhas ganhares, melhor, vais ver, porque depois vais poder trocar essas estrelinhas por um prémio. E sabes que prémios são esses? São fantásticos! Podes jogar um jogo, podes ouvir uma música, cantar uma canção, ou podes ver um filme. Muito divertido! Vamos a isso?

Assistant presentation - contact game

Olá! Olá! Eu sou o Palhaço Barnabé.

Venho do Circo do Arco-íris especialmente para brincar contigo o jogo das letras! Vou pedir-te para brincares com letras e vais ganhar estrelinhas! Que maravilha! E quanto mais estrelinhas ganhares, melhor, vais ver, porque depois vais poder trocar essas estrelinhas por um prémio. E sabes que prémios são esses? São fantásticos! Podes jogar um jogo, podes ouvir uma música, cantar uma canção, ou podes ver um filme. Muito divertido! Vamos a isso?

Two-mission challenge presentation

1 Hoje temos um desafio onde tu tens que realizar 2 missões e eu vou dar-te a energia dos Palhaços!

2 Temos um desafio e tu tens que realizar duas missões, e eu, vou ajudar-te.

Three-mission challenge presentation

1 Hoje temos um desafio onde tu tens que realizar 3 missões e eu vou dar-te a energia dos Palhaços!

First mission presentation

1 Vamos então para a nossa 1ª missão! De cada vez vais brincar com uma letra de uma maneira especial. Primeiro vou mostrar-te como é, e depois fazes tu! Vou ver se tens tanto jeito como eu para esta brincadeira! Que alegria! E eu estou aqui ao teu lado, e vou sempre ajudar-te. Primeiro vamos ver.

2 Vamos então para a nossa 1ª missão. Já sabes que vais brincar com letras de uma maneira especial. Primeiro vou mostrar-te como é, e depois fazes tu! Vou ver se ainda sabes fazer. Vamos lá à nossa brincadeira! Que alegria! Eu estou aqui ao teu lado, e vou sempre ajudar-te, mas primeiro vamos ver.

Second mission presentation

1 Agora, vamos para a nossa 2ª missão! Mais letrinhas para brincarmos. Que divertido! E eu sempre ao teu lado a ajudar-te! Vamos ver.

2 Olha, agora vamos para a nossa 2ª missão! Mais letrinhas para brincares! Mas já sabes, eu ajudo-te. Vamos ver.

3 Olha, agora vamos para a nossa 2ª missão! Mais letrinhas para brincar. São as letrinhas que temos no circo do arco-íris. Vamos ver.

Third mission presentation

Agora vamos para a nossa 3ª missão! Estamos quase, quase no fim [voz lamentosa]. Oh, foi tão divertido... Mas vamos ver.

Demonstration presentation

1 Cá estamos! Vê com muita atenção o que é para fazer, para ficares a saber fazer, tão bem como eu!

2 Vê com muita atenção como se faz, para ficares a saber tão bem como todos os palhaços!

3 Vou mostrar-te como é que um verdadeiro palhaço faz! Vamos ver.

4 Vou mostrar-te como é que um verdadeiro palhaço faz no circo do Arco-íris!

Indication to start the a tracing/moving scene

1 Agora é tua vez! Faz tu para ganhares uma estrelinha!

2 Vamos, agora faz tu, para ganhares uma estrelinha

3 Queres mais uma estrelinha? Então, faz tu!

4 É a tua vez! Faz como eu te mostrei para ganhares mais uma estrelinha.

Congratulations after successful completion of tracing/moving task

1 Muito bem! Ganhaste uma estrela!

2 Oh que bom! Ganhaste mais uma estrela!

3 Excelente! Ganhaste uma estrela!

4 Iupi! Ganhaste mais uma estrela!

5 Fantástico! Ganhaste uma estrela!

6 Ficou óptimo! Tens mais uma estrela!

Copying task presentation (draw game)

1 E agora, para terminares esta missão, só tens que copiar esta letra. Que divertido!

Fazes a cópia onde anda a mãozinha; quando acabares carregas no quadradinho azul. Mas só quando acabares.

2 E agora, para terminares esta missão, só falta copiares esta letra. Vai ser tão engraçado!

Fazes a cópia onde anda a mãozinha; quando acabares carregas no quadradinho azul. Mas só quando acabares.

Free-moving task presentation (contact game)

Agora, para terminares esta missão, só tens que levar esta letra até ao sítio onde anda a mãozinha. Faz como quiseres. Quando acabares, carregas no quadradinho azul. Mas só quando acabares.

Diverte-te!

Copying task presentation end line

1 Estás a postos? Boa cópia!

2 Vamos a isso. Boa cópia!

3 Podes começar. Boa cópia!

4 Vamos lá. Boa cópia.

Acknowledgement for copying task completion

Obrigado! Espero que tenhas feito uma cópia muito bonita!

Acknowledgement for free-moving task completion

Espero que tenhas gostado desta brincadeira!

Congratulations at the end of a challenge (when children won all six stars)

1 Parabéns! Completaste todas as missões e por isso ganhaste todas as estrelas que havia para ganhar! Que bom!

Carrega no presente e depois, põe as estrelinhas lá dentro. E vê o que acontece...

2 Parabéns! Completaste todas as missões e por isso ganhaste todas as estrelas que havia para ganhar! Que bom! Carrega no presente e depois, põe as estrelinhas lá dentro. E vê o que acontece...

3 Que maravilha! Completaste todas as missões. Carrega no presente e depois, põe as estrelinhas lá dentro. E vê o que acontece...

Instructions to choose and collect the prize when children won all six stars

Agora podes escolher o teu prémio! Se carregares no Mágico Artur, ele deixa-te jogar um jogo. Se carregares na Princesa Filipa, ela toca uma canção. E se carregares no Palhaço Barnabé, ele mostra-te um filme. Podes escolher.

Instructions to collect the prize when children won less than six stars

Chegaste ao fim, mas fizeste alguns erros... Que pena. Não tens as estrelinhas todas. Mas podes trocar as tuas estrelinhas por uma canção. Carrega na Princesa Filipa e ouve a canção que ela escolheu para ti.

Goodbye at the end of the game

1 Acabámos por hoje. Tenho que voltar ao circo. Até amanhã.

2 Já acabámos. Agora tenho de ir a correr para festa dos Palhaços do Nariz Grande. [Gargalhada] Até amanhã.

3 Já acabámos. Vou ter com a princesa Filipa e com o Mágico Artur. Até amanhã!

4 Até à próxima! Vou para a festa com as letras que aprendeste hoje.

Princess Filipa

Assistant presentation - draw game

Olá! Eu sou a Princesa Filipa. Venho do palácio das princesas do Reino do Arco-íris especialmente para brincar contigo o jogo das letras! Vou pedir-te para fazeres letras e sempre que fizeres vais ganhar estrelinhas! Que maravilha! E quanto mais estrelinhas ganhares, melhor, vais ver, porque depois vais poder trocar essas estrelinhas por um prémio. E sabes que prémios são esses? São fantásticos! Podes jogar um jogo, podes ouvir uma música, cantar uma canção, ou podes ver um filme. Muito divertido! Vamos a isso?

Assistant presentation - contact game

Olá! Eu sou a Princesa Filipa. Venho do palácio das princesas do Reino do Arco-íris, especialmente, para brincar contigo o jogo das letras! Vou pedir-te para brincares com letras e vais ganhar estrelinhas! Que maravilha! Quanto mais estrelinhas ganhares, melhor, vais ver, porque depois vais poder trocar essas estrelinhas por um prémio. E sabes que prémios são esses? São fantásticos! Podes jogar um jogo, podes ouvir uma música, cantar uma canção, ou podes ver um filme. Muito divertido! Vamos a isso?

Two-mission challenge presentation

1 Temos um desafio onde tu tens que realizar duas missões. E eu, vou dar-te a força das Princesas!

2 Temos um desafio e tu tens que realizar duas missões, e eu, vou ajudar-te.

Three-mission challenge presentation

1 Temos um desafio onde tens que realizar três missões! E eu vou dar-te a força das Princesas!

2 Temos um desafio onde tu tens que realizar três missões, e eu, vou ajudar-te!

First mission presentation

1 Vamos então para a nossa 1ª missão! De cada vez, vais brincar com uma letra de uma maneira especial. Primeiro vou mostrar-te como é, e depois fazes tu! Vou ver se tens tanto jeito como eu para esta brincadeira! Que alegria! Eu estou aqui ao teu lado, e vou sempre ajudar-te. Primeiro, vamos ver.

2 Vamos então para a nossa 1ª missão de hoje. Já sabes que vais brincar com letras de uma maneira especial. Primeiro vou mostrar-te como é, e depois fazes tu. Vou ver se ainda sabes fazer. Vamos lá à nossa brincadeira! Que alegria! Eu estou aqui ao teu lado, e vou sempre ajudar-te, mas primeiro, vamos ver.

Second mission presentation

1 Agora, vamos para a nossa 2ª missão! Mais letrinhas para brincarmos. Que divertido! E eu sempre ao teu lado a ajudar-te! Vamos ver.

2 Olha, agora vamos para a nossa 2ª missão! Mais letrinhas para brincares! Mas já sabes, eu ajudo-te. Vamos ver.

3 Olha, agora vamos para a nossa 2ª missão! Mais letrinhas para brincares! São as letrinhas que temos no reino do arco-íris. Vamos ver.

Third mission presentation

Agora vamos para a nossa 3ª missão! Oh, estamos quase, quase no fim… [voz lamentosa] Foi tão divertido. Mas vamos ver.

Demonstration presentation

1 Cá estamos! Vê com muita atenção o que é para fazer, para ficares a saber fazer, tão bem como eu!

2 Cá estamos! Vê com muita atenção como se faz, para ficares a saber fazer tão bem como todas as princesas!

3 Vê com muita atenção como se faz, para ficares a saber fazer tão bem como todas as princesas!

4 Primeiro, vou mostrar-te como é que uma verdadeira princesa faz! Vamos ver.

5 Primeiro, vou mostrar-te como é que uma verdadeira princesa faz, no reino do arco-íris!

6 Cá estamos. Vê com muita atenção como é as princesas fazem no reino do arco-íris.

Indication to start tracing/moving scene

1 Agora é tua vez! Faz tu para ganhares uma estrelinha!

2 Vamos, agora faz tu para ganhares uma estrelinha

3 Queres mais uma estrelinha? Então faz tu!

4 É a tua vez! Faz como eu te mostrei para ganhares mais uma estrelinha.

Congratulations after successful completion of tracing/moving task

1 Muito bem! Ganhaste uma estrela!

2 Oh que bom! Ganhaste mais uma estrela!

3 Excelente! Ganhaste uma estrela!

4 Iupi! Ganhaste mais uma estrela!

5 Fantástico! Ganhaste uma estrela!

6 Ficou óptimo! Tens mais uma estrela!

	Copying task presentation (draw game)	**Free-moving task presentation (contact game)**
1	E agora, para terminares esta missão, só falta copiares esta letra. Vai ser tão engraçado. Fazes a cópia onde anda a mãozinha; quando acabares carregas no quadradinho azul. Mas só quando	Agora, para terminares esta missão, só tens que levar esta letra até ao sítio onde anda a mãozinha. Faz como quiseres. Quando acabares, carregas no quadradinho azul. Mas só quando acabares.

	acabares.	Diverte-te!
2	E agora para terminares esta missão, só tens que copiar esta letra. Que divertido! Fazes a cópia onde anda a mãozinha; quando acabares carregas no quadradinho azul. Mas só quando acabares.	

Copying task presentation end line

1 Estás a postos? Boa cópia!

2 Vamos a isso. Boa cópia!

3 Podes começar. Boa cópia!

Acknowledgement for copying task completion

Obrigada! Espero que tenhas feita uma cópia muito bonita.

Acknowledgement for free-moving task completion

Espero que tenhas gostado desta brincadeira!

Congratulations at the end of a challenge (when children won all six stars)

1 Parabéns! Completaste todas as missões e por isso ganhaste todas as estrelas que havia para ganhar! Que bom!
Carrega no presente e depois põe as estrelinhas lá dentro e vê o que acontece...

2 Parabéns! Completaste todas as missões, e no reino do arco-íris todas as princesas estão contentes. Carrega no presente e depois põe as estrelinhas lá dentro e vê o que acontece...

3 Que maravilha! Completaste todas as missões. Carrega no presente e depois põe as estrelinhas lá dentro e vê o que acontece...

Instructions to choose and collect the prize when children won all six stars

Agora podes escolher o teu prémio! Se carregares no Mágico Artur, ele deixa-te jogar um jogo. Se carregares na Princesa Filipa, ela toca uma canção. E se carregares no Palhaço Barnabé, ele mostra-te um filme. Podes escolher.

Instructions to collect the prize when children won less than six stars

1 Chegaste ao fim, mas fizeste alguns erros... Que pena. Não tens as estrelinhas todas. Mas podes trocar as tuas estrelinhas por uma canção. Carrega na Princesa Filipa e ouve a canção que ela escolheu para ti.

2 Chegaste ao fim, mas fizeste alguns erros... Da próxima vez vais ver que corre melhor. No reino do arco-íris todas as princesas estarão do teu lado a dar-te força para correr melhor. Agora, podes ouvir uma canção. Carrega na princesa Filipa e ouve a canção que ela escolheu para ti.

Goodbye at the end of the game

1 Acabámos por hoje. Tenho que voltar ao palácio. Até amanhã.

2 Já acabámos. Agora tenho que ir a correr para a festa da rainha da Primavera. Até amanhã.

3 Já acabámos. Vou ter com o palhaço Barnabé e com o Mágico Artur. Até amanhã!

4 Até à próxima! Vou para uma festa com as letras que aprendeste hoje.

3. Error feedback (by error type)

no-start	Não começaste.
wrong-start	Não é aí que se começa.
raising-finger	Não podes levantar o dedo antes de acabar.
going-back	Não podes voltar para trás.
going-out (draw game)	Não podes sair fora da letra.
going-out (contact game)	Não podes sair da linha.
wrong-way	Não é por aí.
no-next	Não acabaste. Tens de acabar a letra.

Appendix II - Informed consent

Caro(a) Encarregado(a) de Educação,

Vimos desta forma pedir consentimento para que o seu educando participe num estudo com o objectivo de avaliar a importância da escrita manual na aprendizagem das letras.

Este estudo enquadra-se na minha tese de mestrado em Ciência Cognitiva orientada pela Professora Doutora Tânia Fernandes e pelo Professor Doutor Luís Correia da Universidade de Lisboa.

A participação envolve três fases. Na primeira, as crianças realizam tarefas simples de papel e lápis que nos permitam garantir que não têm ainda um conhecimento consolidado das letras. Na segunda, as crianças realizam um jogo em *tablet* com letras em períodos de cerca de 20 minutos por dia (durante 20 dias). Na terceira fase, realizam tarefas simples em computador que nos irão permitir avaliar a eficácia deste treino.

Todas as fases serão realizadas na Escola em horário a definir com as educadoras, de modo a não interromper as actividades escolares.

Os dados recolhidos têm natureza confidencial e não serão disponibilizados a terceiros, sendo apenas tratados com fins de investigação. Para as tarefas que iremos realizar, sempre que seja possível comparar o desempenho do seu educando com o nível esperado para crianças portuguesas da mesma idade, forneceremos informação adicional no caso de resultados inesperados. Os dados serão destruídos 36 meses após o término do estudo.

A participação neste estudo é voluntária e a vontade da criança será respeitada. Mesmo que consinta na participação do seu/sua educando/a, se a criança quiser desistir poderá fazê-lo a qualquer momento.

Caso pretenda esclarecimento adicional, por favor contacte-me por e-mail.

Esta informação ficará na sua posse. Caso concorde com a participação, por favor preencha os dados a seguir ao tracejado e entregue-os à [professora/educadora/outro].

Muito obrigada.

Eu, ____,

encarregado de educação de ____

______________________, aluno/a da [Nome da Escola] ____________________________, autorizo a participação do meu educando / da minha educanda no estudo acima descrito e declaro que compreendi a explicação que me foi fornecida.

Data: ____ / ___ / 2016