Cross-transfer of motor control in visuomotor tasks. Systematic review

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Summary

Introduction: The term "cross-education" describes the perfomance improvement, both in motor control and strength, of a limb after training the opposite. Despite its current interest, there is no consensus on many concepts of the transfer of a visuomotor skill. The aim of the present research was to review the current literature on the phenomenon of cross-education in visuomotor skills in order to determine the magnitude of transference and its relationships with the context of the intervention.
Results: A literature search was conducted during December 2019 in the databases Pubmed, CINAHL, MEDLINE, Web of Science, SPORTdiscus and Scopus. The descriptors "Motor ability" and "Motor skill" were used, in addition to the keywords "Motor control", "skill", "Task", "cross over effect", "cross exercise", "contralateral learning", "inter limb transfer "," cross transfer "," cross education ". After applying the inclusion and exclusion criteria, a total of 19 articles were obtained for analysis. Of these articles, 12 are RCTs, 4 crossover clinical trial, 2 are non-randomized trials and only 1 lacks a control group. Most of the articles consist of a short-term intervention. Only 5 studies are of a duration of between 4 and 6 weeks.
Conclusion: the cross-education phenomenon occurs in visuomotor skills. However, the magnitude of transference and its relation to the amount of learning of the trained member seems to be very variable depending on the context of the intervention. Likewise, the scarce consensus and the methodological differences in the studies make it difficult to draw firm conclusions about the effects of the context on the transference.

Key words:
Cross-transfer. Cross-education. Interlimb-transfer. Crossover effect. Motor control. Ability. Visuomotor.

Transferencia cruzada en el control motor en tareas visuomotoras. Revisión sistemática

Resumen

Introducción: El término *cross-education* describe la mejora de rendimiento, tanto en control motor como en fuerza, de un miembro tras el entrenamiento del contrario. A pesar de su actual interés, no existe consenso en muchos conceptos de la transferencia de una habilidad visuomotora.
Objetivo: El objetivo del presente estudio fue revisar la literatura actual sobre el fenómeno *cross-education* en habilidades visuomotoras para determinar la magnitud de transferencia y sus relaciones con el contexto de la intervención.
Resultados: Se realizó una búsqueda bibliográfica durante diciembre de 2019 en las bases de datos Pubmed, CINAHL, MEDLINE, Web of Science, SPORTdiscus y Scopus. Se emplearon los descriptores "Motor ability" y "Motor skill", además de las palabras clave "Motor control", "skill", "Task", "cross over effect", "cross exercise", "contralateral learning", "inter limb transfer", "cross transfer", "cross education". Tras la aplicación de los criterios de inclusión y de exclusión, se obtuvo un total de 19 artículos para realizar el análisis. De estos artículos, 12 son ECA, 4 ensayos clínicos cruzados, 2 son ensayos no aleatorizados y solo 1 carece de grupo control. La mayoría de artículos constan de una intervención a corto plazo. Tan solo 5 estudios son de una duración de entre 4 y 6 semanas.
Conclusión: El fenómeno *cross-education* ocurre en habilidades de tipo visuomotor. Sin embargo, la magnitud de transferencia y su relación con la cantidad de aprendizaje del miembro entrenado parecen muy variables dependiendo del contexto de la intervención. Asimismo, el escaso consenso y las diferencias metodológicas de los estudios dificultan extraer conclusiones contundentes acerca de los efectos del contexto sobre la transferencia.

Palabras clave:
Cross-transfer. Cross-education. Interlimb-transfer. Crossover effect. Control Motor. Habilidad. Visuomotor.

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Introduction

The term *cross-education*, referred to in this review as transfer and cross-transfer, was coined by Edward Wheeler Scripture[1] in 1894. It defines the improvement in the performance (strength and motor control) of a limb after training the opposite counterpart, even though currently these tend to be considered two separate entities[2,3].

There are two main theoretical models which justify the phenomenon: cross activation and bilateral access[2]. Cross activation maintains that adaptations in both cerebral hemispheres are driven by bilateral cortical activity generated during unilateral training (cross facilitation), relating the transfer of a task to the neuronal load it generates[2]. Bilateral access holds that motor engrams developed during unilateral training are not specific to the trained side and are accessible for both limbs[2].

Aspects of cross-education are still being studied. Originally it was thought that transfer does not occur symmetrically, determining that there would only be transfer from the dominant hemisphere[4,5], associating this asymmetry with hemispheric specialisation[6]. Another focus of attention regarding which consensus does not exist is the influence of neuronal degenerative changes. While some studies conclude that transfer is minimal in older subjects[7,8], others, based on the reduction in hemispheric laterality outlined in the HAROLD model (*Hemispheric Asymmetry Reduction in Older Adults*)[9], point to transfer similar to that found in younger people[10,11]. Although many reviews analyse the scale of strength transfer and its relationship with the learning percentage of the trained limb, there are no recent reviews which reflect the magnitude of this relationship in motor control.

In recent years, the attention which the phenomenon of cross-transfer has received has increased, as has the number of trials focussing on it[12]. This is due to its clinical potential and possible application in the rehabilitation of multiple conditions which involve the inability or difficulty to move a limb, be it for musculoskeletal or neurological reasons.

Given the potential of this tool and the limited consensus on it, the objective of this study is to review the current literature on cross-transfer in visuomotor skills to determine the scale of transfer and its relationships with the context of the task and the patient.

Materials and methods

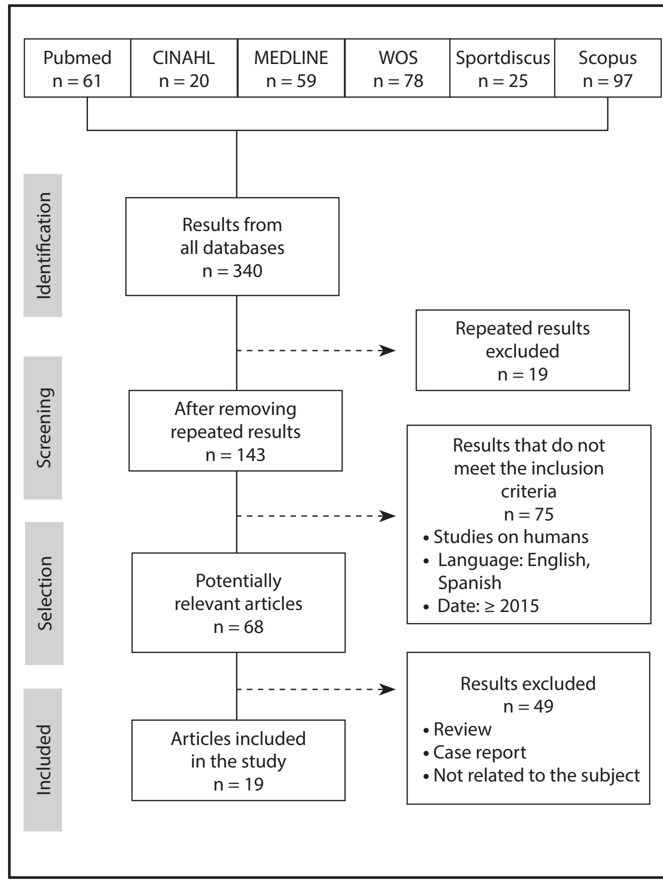
Search strategy

A bibliographic search was carried out in the Pubmed, CINAHL, MEDLINE, Web of Science, SPORTdiscus and Scopus databases between 20 May and 4 June 2021, including all the studies published from 2015 to the present. The search formulas and terms were as follows:

Medline, Cinahl, Pubmed, Sportdiscus: (THESAURUS* *OR "Motor skill" OR "Motor control" OR "skill" OR "Task"*) AND (*"cross over effect" OR "cross exercise" OR "contralateral learning" OR "inter limb transfer" OR "cross transfer" OR "cross education"*).

– *Pubmed: "Motor Skills"(Mesh).*

Figure 1. Study selection flow diagram.



– Medline, Cinahl: *MH "Motor Skills".*
– Sportdiscus: *DE "MOTOR ability".*
– Scopus and Web of Science: *TITLE-ABS-KEY (("Motor skill" OR "Motor control" OR "skill" OR "Task") AND ("cross over effect" OR "cross exercise" OR "contralateral learning" OR "inter limb transfer" OR "cross transfer" OR "cross education")).*

To establish which results were valid for review, a set of criteria was applied following the selection process shown in Figure 1.

Results

Table 1 shows the characteristics of the papers in terms of sample, design and duration of the studies, together with an analysis of their methodological quality.

The mean of the samples is 35 individuals. Most of the studies involve young patients (22-26 years old).

All the interventions bar 8 [14,18,19,21,27-30] are based on tracking trajectories, points or positions. Only 5 of the studies are long-term (4-10 weeks)[3,19,27,29,30]. Only 4 papers focus purely on the lower limbs (LL)[22-24,26]. Only 5 of the studies include a washout period (1-2 weeks)[3,20,21,25].

Table 1. Summary of the methodology of the studies analysed.

	Design	Jadad	Sample	Duration	Washout period
Leung *et al.*[13]	RCT	1/5	N=44 (24♂ and 20♀) A=26.1± 6.8 years old	2 days	2 weeks
Dickins *et al.*[14]	CCT	1/5	N=40 (20♂ and 20♀) A = EG1: 24.25 years old EG2: 70.00 years old	2 days	
Graziado *et al.*[15]	NRCT	0/5	N=24 A = EG1: 28 ± 2 years old EG2: 67 ± 9 years old	1 day	
Pan *et al.*[16]	RCT	1/5	N=40 (17♂ and 23♀) A= EG1: 71.9 ±9.6 years old EG2: 70.4 ±6.8 years old	1 day	
Sainburg *et al.*[17]	NRCT	1/5	N=11 (3♂ and 8♀) A=20-25 years old	2 days	
Steinberg *et al.*[18]	RCT	3/5	N=80 (39♂ and 41♀) A=24.87 ±4.14 years old	4 days	
Christiansen *et al.*[19]	RCT	2/5	N=24 (24♂) A=24±4 years old	6 weeks 3 sessions/week	
Bo *et al.*[20]	NCT	0/5	N=27 (10♂ and 17♀) A=18-34 years old	2 days	10 days
Kidgell *et al.*[21]	CCT	2/5	N=14 (8♂ and 6♀) A=22.6± 6.6 years old	3 days	1 week for different tasks
Krishnan *et al.*[22]	RCT	1/5	N= 20 A=22.8± 5.8 years old	1 day	
Krishnan *et al.*[23]	RCT	1/5	N= 44 (18♂ and 26♀) A= EG1: 67.2 ± 4.1 years old EG2: 24.8 ± 6.9 years old	2 days	
Yen *et al.*[24]	RCT	1/5	N= 20 (7♂ and 13♀) A= EG1: 24 ± 4.4 years old EG2 22.2 ± 0.4 years old	1 day	
Leung *et al.*[3]	RCT	1/5	N= 43 (21♂ and 22♀) A=26.4 ± 6.9 years old	4 weeks 3 sessions/week	2 weeks
Neva *et al.*[25]	CCT	1/5	N=17 A=24 ± 3 years old	4 days	2 weeks
Krishnan[26]	RCT	1/5	N=45 (25♂ and 20♀) A=22.3 ± 5.7 years old	1-2 days (according to EG)	
Witkowski *et al.*[27]	RCT	1/5	N=32 (16♂ and 16♀) A=14-20 years old	10 weeks	
Wang *et al.*[28]	RCT	1/5	N=24 (16♂ and 8♀) EG1: 27.3 ± 4.4 years old EG2: 20.7 ± 3.8 years old	1 day	
Beg *et al.*[29]	RCT	3/5	N=50 (20♂ and 30♀) A=23.4 ± 2.5 years old	4 weeks 2 sessions/week	
Brocken *et al.*[30]	CCT	2/5	N=68 (68♀) A=9.5-12.5 years old	7 weeks 14 sessions	

♂: male; ♀: female; A: age; RCT: randomised clinical trial; CCT: crossover clinical trial; NRCT: non-randomised clinical trial; NCT: non-controlled trial; N: sample.

Table 2. Intervention and main results.

	Intervention	Variables analysed	Main results
Leung *et al.*[13]	4 EG: CT vs STM vs STwM vs Control CT: match the position of the elbow with that shown on the screen.	1-RM and MVC CSE, SLII	CSE and SLII transfer (p<0.001) SLII differences between EG: STM, CT > STwM, control
Dickins *et al.*[14]	2 EG: old vs young 2 types of CT: Ballistic thumb abduction Finger-to-thumb opposition sequences	CSE Peak velocity correct sequences	Young: better overall performance Transfer in the 2 tasks (p <0.001) Increase in CSE only in the simple task (p = 0.001) with no differences between groups (p> 0.1). No relationship between CSE and transfer (p> 0.1).
Graziado *et al.*[15]	2 EG: old vs young CT: tracking points by electromyographic activity of the abductor pollicis brevis, 3rd dorsal interosseous.	Euclidean cursor-centre distance: - 120 ms after start (distance) - For 1s on reaching the objective (score)	Young: better overall performance Significant transfer (p <0.001) Differences between ages in the distance variable, (significant only in the elderly: p <0.001) Score transfer significant relationship with learning (p = 0.016).
Pan *et al.*[16]	2 EG: healthy and with PN. CT: Point tracking on screen with digital pen.	Initial direction error	Significant transfer (p <0.001), greater in RL than LR (p = 0.003). Less transfer in healthy (p = 0.01). Non-symmetrical transfer in healthy; but symmetrical with PN, RL Group greater after-effects (p=0,045).
Sainburg *et al.*[17]	2 EG: RL vs LR CT: Point tracking using the index.	V_{max} Peak acceleration Acceleration duration	Non-symmetrical Vmax transfer (p = 0.855) Asymmetrical transfer of Peak acceleration (lower in LR, p = 0.0059) and of Acceleration duration (higher in LR, p = 0.0059) No differences after contralateral practice
Steinberg *et al.*[18]	2 EG: mirror vs control 2 subgroups per EG: novices vs experts 2 types of CT with basketball: Stationary dribbling Slalom dribbling	Correct sequences Dribbling error	Significant transfer (p <0.001) with differences according to EG and experience (p <0.05) Only experts differences according to EG: (p <0.01), better with mirror Differences in control groups, greater transfer in novices (p <0.05) No differences between groups with mirror (p> 0.05) Dribbling error transfer without differences (p> 0.05) Transfer in slalom: experts greater with mirror (p <0.05); novices no transfer with mirror (p> 0.05)
Christiansen *et al.*[19]	2 EG: progressive difficulty vs no progression CT: a game called "BreakOut" contro-lled by abduction and adduction of the 5th digit.	CSE "BreakOut" score	Transfer only in progressive EG (p <0.001) Increase in initial CSE without differences (p <0.05) Increase in final CSE only in progressive EG No relationship between CSE and transfer (p> 0.05).
Bo *et al.*[20]	1 EG: with and without motor disability CT: Point tracking with handheld joystick.	DE MT Root mean square error	Transfer not related to ADC score (p> 0.05) DE transfer (p <0.05) in normal feedback and MT transfer (p <0.05) in enhanced feedback. Transfer regardless of feedback (p> 0.05) Relationship between learning and transfer: DE (p <0.02) in normal feedback, MT (p <0.04) in enhanced feedback.
Kidgell *et al.*[21]	3 EG divided into 3 CT: "O'Connor dexterity" "Purdue pegboard" "Mirror Purdue pegboard"	Time to perform the task	Greater transfer in Mirror Purdue (p <0.05). Relationship between learning and transfer in Mirror Purdue (p=0.03)
Krishnan *et al.*[22]	2 EG: RL vs LR CT: Adjust gait pattern to the one indicated in real time on the screen.	Tracking error	Significant transfer (p <0.003) No significant differences between sides (p = 0.247) Relationship between learning and transfer: 84% (p<0.001)
Krishnan *et al.*[23]	2 EG: old vs young CT: Adjust gait pattern to the one indicated in real time on the screen.	Tracking error	Young: better performance Less transfer in the elderly (p <0.05) but without differences in test without visual feedback (p> 0.1) Relationship between learning and transfer (p> 0.001): 79% young; 56% elderly

(continue)

Table 2. Intervention and main results *(continuation).*

	Intervention	Variables analysed	Main results
Yen *et al.*[24]	2 EG: RL vs LR CT: Point tracking using isometric force of the ankle	MT Accuracy	Significant transfer (p <0.01) No differences between sides (p = 0.05)
Leung *et al.*[3]	4 EG: CT vs STM vs STwM vs Control CT: match the position of the elbow with that shown on the screen.	1-RM and MVC CSE, SLII MT	Greater skill transfer in the CT group (GROUP x TIME: p = 0.005) but non-significant relationship between learning and transfer (p> 0.05). Specific transfer similar between EG (p> 0.05). Greater CSE and SLII improvements in CT and STM No relationship SLII or CSE and transfer (p> 0.05).
Neva *et al.*[25]	2 EG: Previous aerobic warm-up* vs Control CT: Point tracking with handheld joystick.	Maximum side shift Angle at peak velocity Response time and MT	Differences between groups during the intervention which were no longer significant by the end (p> 0.05). Significant transfer (p <0.05) Differences between groups in reaction time (p = 0.045) which disappear in retention (p> 0.05).
Krishnan[26]	2 EG: massed practice vs distributed practice CT: Adjust gait pattern to the one indicated in real time on the screen.	Tracking error	Greater transfer in distributed practice (p <0.044). Significant relationship (p <0.001) between learning and transfer (76%).
Witkowski *et al.*[27]	2 EG: CT vs Control Intervention in 3 phases: Whole-body, eye-to-hand and eye-to-foot, specific to fencing	Hand-grip strength Accuracy of hits in 3 different tests	No significant differences in strength (p = 0.05) Significant improvement in 3/3 (p <0.001) Significant transfer in 2/3 (p<0.001 and p<0.01)
Wang *et al.*[28]	2 EG: Left-handed vs Right-handed 2 subgroups: LR vs RL CT: "pegboard task"	Time to perform the task	Significant improvement and transfer (p <0.05) except right hand of the right-handed, no improvement or transfer (p> 0.1) No relationship between learning and transfer (p> 0.1
Beg *et al.*[29]	2 EG: CT vs Control CT: "pegboard task"	Time to perform the task JTT test	Significant improvement and transfer in the task (p <0.05) and in JTT (p <0.05) except in the writing and simulated feeding subtests
Brocken *et al.*[30]	2 EG: EG A: CT, Control EG B: Control, CT CT: training with hockey stick (adapted) with hands switched over	Time to perform the test	Significant improvement and transfer (p <0.016) EG B faster in pre-test (p <0.001); but EG A greater general improvement (p = 0.043). Longer times in pre-test related to greater improvement p= 0.04

RL: cross-transfer from the dominant side; MD: motor difficulties; CT: coordination training; CSE: corticospinal excitability; DE: direction error; STM: strength training with metronome; STwM: strength training without metronome; EG; experimental group; SLII: short latency intracortical inhibition; LR: cross-transfer from the non-dominant side; min: minutes; MVC, maximum voluntary contraction; N: sample; RM: repetition maximum; MT: movement time. V_{max}: peak velocity.

Regarding the heterogeneity of objectives, we find that 3 papers compare transfer in young and old individuals[14,15,23], 5 analyse transfer according to the dominance of the trained limb, 2 studies analyse samples with pathology[16,20], several studies compare interventions of varying difficulty or novelty[14,18,19,21], 2 compare transfer in visuomotor (VT) and strength (ST) training[3,13], only 1 study centres on the influence of previous aerobic warm-up[25], and another focuses on different distributions of practice[26].

All the papers except Leung *et al.*[13] analyse performance. Electrophysiological measurements were taken in 4 studies[3,13,14,19]. While all the studies analysed corticospinal excitability (CSE), only 2 analysed short latency intracortical inhibition (SLII)[3,13].

Discussion

Influence of context on cross-transfer

Difficulty and novelty of the task and transfer

Those papers which analyse the influence of difficulty show improved transfer when the task is challenging for the individual[19,21]. These results support the theoretical proposal whereby the type, novelty and complexity of the task condition transfer[2]. Greater demands for coordination and neuromuscular activation involve greater oxygenation[31] and cortical activation, favouring greater adaptations than simple tasks do[32].

Only Steinberg *et al.*[18] analyse the influence of the novelty of the task on transfer, observing greater effects when the individual is a novice. The greater overall improvement of the novice group with direct feedback could be because the expert group is already at the most advanced stage of learning. At this stage, the sensorimotor map of the task is internalised, and sensory feedback and paying attention to execution are not necessary[33], thereby decreasing the neuronal load and impairing transfer[2]. On the other hand, the benefit gained by the expert group when using the mirror could be because the tasks with normal feedback are considered simple and those viewed in reflection are considered complex. This consideration is described in Kidgell *et al.*[21], where the task considered more complex is the one carried out through reflection in a mirror. This greater complexity forces the subject to focus their attention on both the reflection and execution of the task previously considered simple[2].

Transfer differences according to age

All the studies which include an elderly population find significant transfer[14-16, 23] despite showing lower performance than the younger group during the learning stage[14,15,23]. However, there is no consensus regarding the differences between age groups.

When learning a new gait pattern, older subjects experience less transfer than younger subjects[23]. This is in line with studies which show decreased transfer in the elderly[7,8] due to the mechanisms of neuronal degeneration associated with aging, such as the decrease in CSE[34] and the increase of intracortical inhibition[35], which are both important in the consolidation of motor memory[36]. However, Dickins *et al.*[14] and Graziado *et al.*[15], with interventions focussing on upper limbs (UL), describe transfer as the same[14] or even higher in the elderly[15], which supports the HAROLD model; the aforementioned deficits are compensated by greater bilateral hemispheric recruitment[9].

The greater transfer in the elderly for the variable measuring the feedforward component described by Graziado *et al.*[15] could be due to several factors. While healthy elderly individuals conserve effective predictive adaptability, it remains unclear how this is affected by age[37]. However, findings suggest that the cognitive decline which occurs with age is responsible for the deterioration of predictive control[38]. So, cognitively healthy older individuals could improve and transfer this ability in a similar way to other age groups. On the other hand, the young people may not improve because the part of the task which evaluates anticipation does not pose a sufficient challenge, thereby decreasing transfer and generating a difference between groups. Finally, the lack of consensus on transfer in this population could be partly explained by methodological differences, which modify learning in the elderly population, and by individual characteristics, to which little attention is paid. Personal variables, such as lifestyle, could be protective factors against cognitive and memory decline.

Transfer asymmetry

The findings of the studies on this variable are relatively heterogeneous. While the 2 studies which analyse transfer in LL find that transfer occurs regardless of the trained side[22,24], this factor does condition transfer in UL[16,17,28].

In UL, it is observed that transfer from the dominant limb is greater and adapts better to different tests in the study by Pan *et al.*[16]. This concurs with the ideas advanced by the proficiency model (the dominant side is more effective when adapting to new tasks, transferring more and higher quality information) and hemispheric specialisation (the ability of each hemisphere to produce internal models of different skills)[32]. Specifically, the dominant side benefits from spatial skills[39], as occurs in the paper by Pan *et al.*[16], where a spatial control measurement is analysed. On the other hand, Sainburg *et al.*[17] describe symmetrical transfer but with different adaptations according to the specific function of each hemisphere. This coincides with another study in which the transfer of ball shooting accuracy is symmetrical, but the motor strategies to reach this adaptation differ between sides[40].

Finally, Wang *et al.*[28] obtain an asymmetrical result in right-handers; their right hands do not improve or receive significant transfer, supporting the proficiency model. Left-handers, meanwhile, improve and receive transfer in both hands. This could be due to greater use by the left-handed of the non-dominant arm in their routines, favouring greater interhemispheric connectivity and dexterity with the non-dominant hand than in the right-handed[41].

In the LL studies, symmetrical transfers of spatial control are observed in the gait study[22] and in isometric control of the ankle[24]. The greater symmetry in LL could be explained by less lateralisation of these limbs compared to UL due to the different tasks and motor strategies that distinguish them[42]. Although certain studies concur in confirming LL symmetry[6,43], the evidence which backs this idea is scarce, and there is little consensus on the matter, findings of asymmetry in certain variables also existing[40,42].

Witkowski *et al.*[27] and Brocken *et al.*[30] describe interventions in sports activities which involve equipment designed for use with the non-dominant limb (fencing foil) and with hands switched over (hockey stick), respectively. Both studies observe significant transfer to the dominant side, demonstrating the ability to effectively transfer visuomotor skills from the non-dominant side in asymmetrical sports.

Finally, considering that contextual variables, such as the complexity and novelty of a task, influence the direction of transfer[28], the heterogeneity of the intervention protocols hinders prediction of the symmetry pattern in transfer. This can be seen in Stöckel *et al.*[6], where changing the instructions for the same task leads to variations in transfer from each limb depending on whether the subjects perceive the task as more spatial or more dynamic in nature.

Transfer differences in participants with pathology

The two papers which analyse this variable differ in terms of the pathology involved and, consequently, are not comparable. Nevertheless, they both find significant transfer comparable to that of the healthy group[16,20].

In Pan *et al.*[16], transfer is symmetrical in people with peripheral neuropathy. As this pathology involves degeneration of the somatosensory area [44], the results explained previously could be due to compensatory neural mechanisms in a line similar to that proposed in the HAROLD model and cognitive decline[16].

In Bo *et al*.[20], transfer is similar between people with different motor abilities, suggesting that it is more related to the establishment of motor engrams than motor abilities. Finally, the difference in skill transferred according to feedback could be explained by the observations made in a contemporary study in which the movement time during the task increases as the feedback increases[45]. On this basis, the results of Bo *et al.*[20] could be due to learning about the new condition, movement time improving after adaptation.

Warm-up and practice distribution

In the current literature, it has been observed that spacing out the intervention favours the learning of skills in UL in adults[46]. Despite the paucity of trials in this area with LL, the effect would appear to be the same[47]. In line with these studies, the transfer of a new gait pattern improves with distributed practice[26].

Meanwhile, the temporary improvements in performance after warming up observed by Neva *et al.*[25] differ from the findings of another study in which performance decreases after high intensity exercise[48]. This could be explained by a lower intensity of the warm-up, reducing fatigue when performing the test. On the other hand, temporary changes in reaction times may be due to acute increases in attention after exercise[49], increases in attentional levels facilitating faster reaction times[50].

Scale of performance cross-transfer

All the studies find significant performance improvements in both the trained and the contralateral limb in some of the variables studied[3,14-30]. However, not all the papers indicate the percentage of contralateral improvement. Furthermore, the percentages described vary considerably across the different studies. This could be explained by the different variables analysed and interventions and protocols used in the different studies, leading to greater or lesser transfer and producing data which are not homogeneous.

Scale of long-term transfer

The only 5 studies which analyse long-term cross-transfer find significant transfer at the end of the intervention[3,19,27,29,30]. However, only 2 of them specify the transfer percentages[3,19].

In Leung *et al.*[3], learning and transfer are greater in the group which specifically trains for the task. Although the specific transfer percentage is similar between ST groups (14.4±3.8% to 11.9±4.5% in strength) and VT groups (12.4±2.3% in motor control), the electrophysiological measurements depend on the type of intervention. So, although it is incorrect to say that ST and VT share the same corticospinal responses, they are somewhat similar. On comparing the magnitudes described by Leung *et al*.[3] with similar intervention protocols, these are slightly higher than those described for strength transfer in UL (9.4%)[12]. However, Christiansen *et al*.[19] describe much higher improvement percentages in their progressive training group (76±14%). This could be due to the methodological differences between the two studies. On the one hand, Leung *et al*[3] use a very different task to that of Christiansen *et al.*[19] involving non-progressive difficulty adjustment and compare the results with the control group as Carrol *et al.*[51] suggest in order to reduce the influence of familiarisation with the test. Meanwhile, Christiansen *et al*.[19] do not describe a washout period, their protocol is 2 weeks longer, the sample is smaller, there is no control group, and the variables which measure performance differ greatly between studies.

Relationship between amount of learning and amount of transfer

Most of the studies which analyse this variable, described as a percentage of contralateral improvement with respect to the amount of ipsilateral improvement, obtain significance. However, it is difficult to establish a consensus on this relationship because its magnitude is relatively variable according to the context, as observed in the other sections.

This relationship is significant in the 3 LL studies. The percentages range from 84%[22] to 76%[26] and the result is lower in elderly individuals: 56%[23]. However, all three studies are conducted by the same investigator, with very similar interventions and protocols. Furthermore, two of the studies analyse transfer by comparing the base measurement of the trained limb with the final measurement of the opposite limb, crossing data between limbs and biasing the result. In the UL studies by Bo *et al*.[20] and Graziado *et al*.[15], this relationship is only found in the variables with significant transfer and without differences between groups (homogeneous results). Finally, Kidgell *et al*.[21] only find a correlation with learning in the most difficult task, while Leung *et al*.[3] and Wang *et al*.[28] find no relationship for VT. As occurs in Kidgell *et al*.[21] with the easier tasks, the intervention used in Leung *et al*.[3] may not be difficult enough to produce sufficient improvements to detect significance in the relationship. Similarly, the short duration of the study by Wang *et al*.[28], 4 blocks of practice, may not permit detection of the relationship due to an insufficient amount of improvement.

Electrophysiological measurements

The 2 studies which compare VT and ST transfer find different cortical adaptations between groups. In Leung *et al*.[13], there are only differences between groups for changes in SLII, but none for changes in CSE. However, in a later study, they report greater changes in CSE and SLII in VT and ST with metronome compared to the other groups[3]. This could be explained by the findings of Christiansen *et al*.[19], where both groups initially have equal increases in CSE. However, these changes only last in the group in which the difficulty increases progressively. Thus, in the shorter study, VT and ST may generate the same excitatory changes because when a strength task is new to an individual, there is substantial motor control adaptation regardless of its complexity[32].

In Dickins *et al.*[14], the CSE changes in the simple task but not the complex one could be because neural adaptation is not detected due to it occurring outside the primary motor cortex (M1). This can be explained based on the multiple cortical areas activated in the control of different parameters of the hand grip[52] and on the fact that it is not possible to assume that the interactions between M1 are the origin of cross-facilitation just because the interaction of the two cortices is expressed through M1[2].

Finally, no significant relationship has been found between changes in CSE[3,14,19] or SLII[3] and improved task performance. This is consistent with Ruddy *et al.*[2] when they affirm that cross-facilitation not only occurs in the homologues of the muscles involved in the task but also in the homologues of those which are not. Moreover, this activation lasts over time and is called "post-activation potentiation". Therefore it is wrong to assume that changes in excitability only represent significant adaptive changes.

Conclusions

The studies covered in this review show the presence of motor control transfer in visuomotor tasks in the short and long term. The magnitude and direction of this effect appears to be highly variable, depending on multiple contextual factors, such as state of the nervous system, hemispheric lateralisation and type of task. Similarly, the amount of learning appears to be related to the amount of transfer (albeit variably) but changes in CSE and SLII do not. On another note, the differences between UL and LL are inconclusive due to the limited number of studies reviewed. Finally, the low quality of the studies and general methodological heterogeneity make it difficult to draw firm conclusions from these findings.

It is necessary to conduct more studies of higher methodological quality and with more standardised measurement protocols, recording in more detail individual variables and aspects of the task which could influence transfer. Future trials should also study which factors modify the relationship between amount of learning and transfer to optimise the use of this tool.

Conflict of interest

The authors declare that they are not subject to any type of conflict of interest.

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