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Broadening the lens: A review of multi-object tracking task and its use in cognitive training

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ABSTRACT

The Multiple Object Tracking (MOT) task, recognized for its reliance on attentional control and dynamic visual processing, is a key activity in computerized Cognitive Training (CT). However, the mechanisms driving MOT-based CT and its transfer effects—both near transfer (gains in similar tasks) and far transfer (improvements in unrelated domains)—remain incompletely understood. This narrative review synthesizes existing research on how adjustable MOT parameters, such as target number, object speed, tracking duration, and perceptual features, influence performance and transfer outcomes across populations.

This narrative review aims to (1) identify the cognitive functions engaged by various MOT parameters, (2) determine which adaptations lead to performance gains, and (3) assess how MOT improvements translate into near and far transfer effects, with a focus on real-world applications.

MOT involves divided and sustained attention, foveal and peripheral vision, and inhibitory control, interacting with working memory and executive functions, which encompass high-level cognitive processes such as planning, inhibition, and cognitive flexibility. While speed thresholds and target counts are commonly adjusted, the broader impact of variables like tracking duration remains understudied. Near transfer effects from MOT training consistently enhance attention-related tasks, while far transfer results vary. Some studies suggest that prolonged MOT training improves visuospatial working memory and executive functions, particularly with longer tracking durations. However, inconsistencies across studies highlight how task design and population characteristics influence outcomes. Despite limited research on ecological validity, previous studies have highlighted benefits for dual-task performance, particularly in cognitive-motor coordination in sports (Fleddermann et al., 2019; Pothier et al., 2015). This narrative review underscores MOT-based training's potential but calls for more rigorous evaluation of transfer effects and real-world applicability.

1. Introduction

Cognitive Training (CT) interventions have gained popularity due to their cost-effectiveness and accessibility across age groups. These non-pharmacological programs typically involve repetitive practice of computer-based tasks with the assumption that improvements will either occur in tasks closely related to the trained activity (near transfer) or extend to broader, more distinct tasks (far transfer). However, evidence supporting the CT effectiveness remains mixed, particularly regarding its transfer effects beyond trained tasks (Lampit et al., 2014; Simons et al., 2016; Webb et al., 2018). Although CT programs often produce significant gains in the tasks practiced (Von Bastian & Oberauer, 2013), their impact on real-world functioning is inconsistent (De Simoni & von Bastian, 2018; Guye & von Bastian, 2017), raising questions about the mechanisms that enable transfer and the conditions required for meaningful cognitive improvements.

Some studies report positive ecological transfer effects, particularly when CT targets executive functions such as attentional control or perceptual-cognitive skills (Binder et al., 2016). These benefits have been observed in diverse populations, including children (Bertoni et al., 2019) and older adults (Ballesteros et al., 2020). Tasks involving divided attention or controlled shifting appear especially effective, suggesting

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that task-specific cognitive demands play a crucial role in producing meaningful gains. Among these tasks, the Multiple Object Tracking (MOT) task has emerged as a promising tool in computerized CT programs. In a typical MOT task (Fig. 1), participants track a subset of identical objects moving unpredictably on a screen and must identify the original targets after the movement phase (Scholl, 2009). Adjusting parameters such as the number of targets, object speed, and task duration allows researchers to modulate attentional control demands (A. Holcombe, 2023; Vater et al., 2021). As task difficulty increases, so does the attentional control required. This flexibility makes MOT a valuable activity for designing progressively refined training programs. Evidence suggests that MOT training enhances executive functions and working memory, with benefits extending to areas such as gaming and decision-making. However, the mechanisms underlying attention-based CT and their relationship with transfer effects remain poorly understood (Vater et al., 2021). (See Box 1.)

Existing reviews of MOT, such as those by Meyerhoff et al. (2017) and Holcombe (2023), have primarily focused on specific theoretical cognitive frameworks. In contrast, **this review takes a functional approach, examining** how manipulating task parameters influences cognitive performance across both neurotypical and non-neurotypical populations to offer practical insights into optimizing training programs. Given the heterogeneity in methodologies, participant groups, and outcomes across the literature, our review adopts a flexible framework to evaluate how parameter variations affect both performance and transfer effects. We set no strict publication date limits, allowing a broad field overview while prioritizing recent studies. We included only English-language articles to ensure consistency and accurate interpretation. Diverse methodologies were considered to assess task parameter manipulation, including both 2D and 3D MOT tasks. Focusing on open-access articles ensured accessibility and reproducibility. By selecting theoretical and empirical studies on task parameters, cognitive outcomes, and applicability, we aim to provide actionable insights for improving CT programs. To this end, our objectives are threefold:

1. **To identify the cognitive processes** associated with adjustable **MOT** parameters.
2. **To investigate how variations in MOT task parameters** influence **performance improvements** and their **training outcomes** (including near and far transfer effects).
3. **To determine which enhancements in MOT performance** lead to **genuine transfer effects**, particularly in real-life contexts.

Box 1: Takeaway messages on MOT

Numerous studies in visual and attentional research have employed the cognitively multi-determined MOT task:

- The FINST Model's pioneering concept (Z. Pylyshyn, 1994) identified MOT as a process potentially guided by **pre-attentive stimuli**, using a mechanism that tracks multiple objects without detailed attention or conscious recognition. The brain assigns visual spatial indexes to a limited number of objects in the visual field.
- The Grouping Theory (Yantis, 1992) sheds light on the visual system's capacity to simplify tracking by **unitizing individual targets into a cohesive visual entity**.
- The FLEX Model (Alvarez & Franconeri, 2007) introduced the idea of a **malleable pool of attentional resources that adjusts dynamically to the demands of tracking complexity**.
- While earlier theories like the **Spatial Interference Theory** (Franconeri et al., 2010) emphasized spacing-related limits, the field has since shown that **both spatial crowding** (studied extensively in visual psychophysics) and **temporal frequency** constrain MOT performance. This highlights the need to consider the combined impact of spatial and temporal interferences rather than relying on single-factor explanations.
- The Holcombe and Chen (2013)'s work underscored the limitations of tracking resources, countering the notion that spatial interference alone affects tracking accuracy.
- The Multifocal Attention Theory (Cavanagh & Alvarez, 2005) explored the possibility that multiple attentional beams can be directed towards **different objects simultaneously**, enhancing the understanding of how attention is distributed in MOT tasks.
- The correlation-based studies (typical and non-neurotypical individual-differences approach) revealed a strong to moderate bond with the visual processing, **dynamic attention**, **selective**, **sustained** and **divided** attention, as well as with **working memory**.

Overall, MOT does not tap a monolithic cognitive function but a complex dynamic interplay of visual processing, attentional resources, and working memory, shaped by both the intrinsic properties of the objects being tracked and the overarching conditions of the task.

Box 1. Takeaway messages on MOT.

We include and compare the effects of task manipulations **among** neurotypical and non-neurotypical (neurodiverse) populations. Neurodiverse groups, as defined by Doyle (2020), include individuals with attentional/executive disorders, mental health conditions, neurological disorders, and sensory impairments. This comparison aims to **leverage individual differences in cognitive mechanisms** to refine the functional analysis of MOT, both in terms of **underlying cognitive processes** and **training outcomes** (e.g., transfer effects).

Overall, we address three research questions:

Q1. How do MOT parameter changes directly shape task performance (e.g., tracking accuracy, response time), and what cognitive mechanisms underlie these effects? How do non-neurotypical populations illuminate

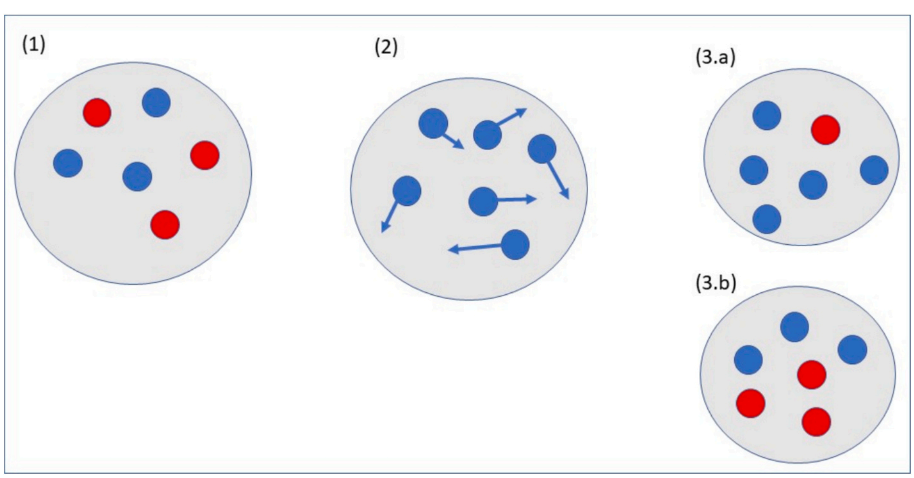


Fig. 1. An example of a variant of the multi-object tracking task (1) Three discs are briefly colored red in red to mark them as tracking targets. (2) All items look the same and move around randomly on the screen. (3) (a) At the end, one item is highlighted and the participant reports if it was a target or not. (3) (b) At the end of the motion phase, the participant must recognize the initial discs identified as targets. Animations of many different variants of this task can be viewed at or downloaded from https://perception.yale.edu/Brian/demos/ MOT.html. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the fundamental processes driving MOT tasks?

Q2. How does MOT-based CT induce performance improvements in the trained task (near-transfer effects), and do parameter adjustments during CT modulate these improvements? How does MOT practice influence cognitive functioning across the transfer spectrum (from near to far transfer) in neurotypical and non-neurotypical populations?

Q3. What real-world transfer effects (e.g., decision-making, daily functioning) emerge from MOT training in neurotypical individuals, and how do non-neurotypical conditions alter these effects?

1.1. Cognitive underpinnings of MOT task according to adjustable parameters

Q1. How do changes in parameters affect performance in MOT tasks, and what cognitive mechanisms explain these effects?

Understanding the mechanisms behind the MOT task relies on two complementary psychological approaches. The first is cognitive psychology, which uses an analytical method to identify cognitive mechanisms by manipulating task parameters (e.g., number of targets). The second is differential psychology, which adopts an individual-differences approach. This involves studying correlations between MOT performance and tests of specific cognitive functions (e.g., working memory, executive functions), as well as how individual differences in these functions (e.g., perception, attention) influence MOT outcomes. These approaches differ in the granularity of their insights: cognitive psychology offers a fine-grained analysis of processes, while differential psychology provides a broader perspective focused on major cognitive functions like perception, attention, and memory. Together, they help distinguish which cognitive functions and mechanisms are unique to the MOT task and which are shared with other tasks.

2. Analytical approach by MOT parameters manipulations

Many studies have explored the MOT task as a phenomenon by examining parameters that influence performance and the underlying cognitive processes (Meyerhoff et al., 2017). Key parameters identified as either facilitators or barriers to MOT task success include the number of targets, their speed, the tracking duration and the perceptual characteristics of targets within the task environment. A non-exhaustive set of studies manipulating MOT parameters as a way to better understand tracking mechanisms is proposed in Fig. 2.

2.1. The critical triad of parameters

The number of targets, their speed, as well as the duration of tracking are the most studied parameters of MOT.

2.2. Numbers of targets

The number of targets to be tracked is a key parameter in MOT performance and was first manipulated by Pylyshyn and Storm (1988) to test the FINST theory. This model suggests that the brain assigns visual spatial indexes (FINSTs) to a limited number of objects in the visual field, acting as perceptual “fingers” that attach to objects and enable their tracking without requiring detailed attention or conscious recognition of their features (Pylyshyn, 1994). These low-level processes allow tracking to occur pre-conceptually, without relying on memory representations. Initially described as pre-attentive (Pylyshyn & Storm, 1988), this term was later refined to preconceptual to better account for the role of attention, especially as target quantity increases (Meyerhoff et al., 2017; Pylyshyn, 2001). Subsequent studies, including Alvarez’s FLEX model (Alvarez & Franconeri, 2007) and research by Horowitz and Cohen (2010), have consistently demonstrated a set size effect: as the number of targets increases, tracking performance declines. Oksama and Hyönä (2004) observed that, with constant tracking time, performance drops follow linear (87.6 %), quadratic (6.6 %), and cubic (5.3 %) trends. The linear trend contradicts Pylyshyn and Storm’s (1988) claim of purely parallel tracking, which assumes stable performance up to the FINST limit. In contrast, the nonlinear trends suggest that attention may shift between targets, indicating a degradation in attention allocation over time. These results contribute to the debate between serial and parallel processing models and introduce the concept of multifocal attention, where multiple attentional beams may be directed simultaneously toward different objects (Alvarez & Cavanagh, 2005).

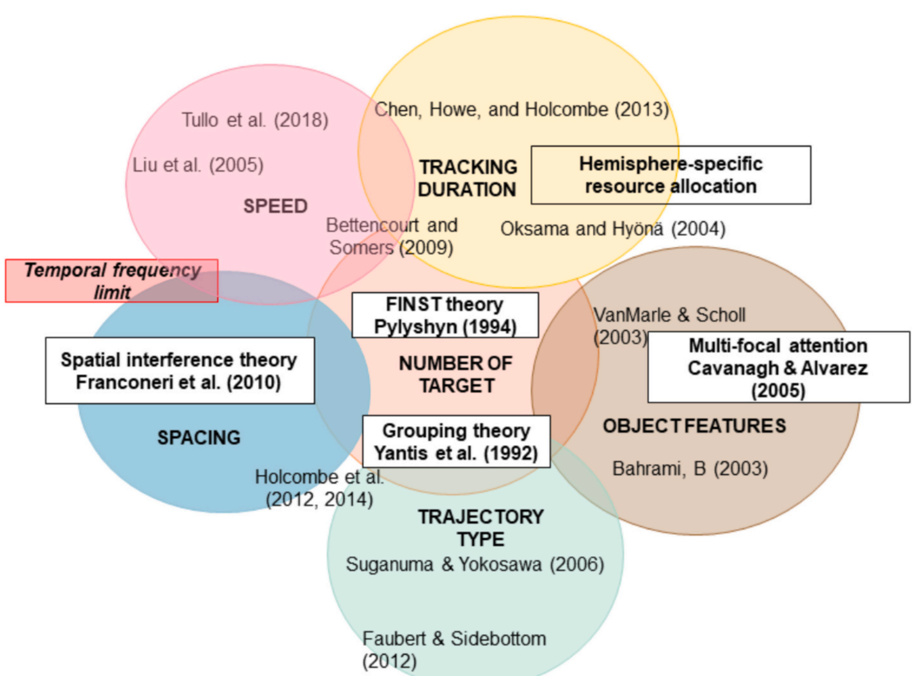


Fig. 2. A non-exhaustive set of studies manipulating MOT parameters as a way to better understand tracking mechanisms.

2.3. Speed

The speed parameter refers to the pace at which targets and distractors move across the display. Tracking accuracy declines systematically as object speed increases (G. Liu et al., 2005). Alvarez and Franconeri (2007) found a **logarithmic relationship** between speed thresholds and the number of tracked objects: as target quantity increased, speed thresholds decreased. Participants could track up to eight targets if speeds were adjusted to their abilities, suggesting that tracking resources are more adaptable than initially assumed. This adaptability is central to the **FLEX model** proposed by Alvarez and Franconeri (2007), which posits that tracking relies on a **continuous, flexible pool of resources** that adjusts based on task difficulty. Bettencourt and Somers (2009) further demonstrated that at **lower speeds and shorter tracking durations,** objects often remain near their initial positions, engaging **visual short-term memory (VSTM)** more than dynamic tracking. Their findings revealed that performance consistently drops at **higher speeds**, reinforcing the notion of resource flexibility in tracking.

Speed also impacts **hemisphere-specific resources**, as noted by Chen et al. (2013). Unlike VSTM, which is largely shared across hemispheres, object tracking depends on **hemisphere-specific attentional resources**. This distinction highlights the cognitive challenge of balancing tracking demands across hemispheres in dynamic tasks. Thus, the effect of speed reflects not only the **increased cognitive load** but also, the need to manage **resource allocation** within each hemisphere (Chen et al., 2013).

2.4. Tracking duration

Tracking duration significantly impacts MOT difficulty. Oksama and Hyönä (2004) observed the steepest performance drop between 5 and 9 s, with error rates increasing from 9.0 % to 19.5 %, followed by a plateau between 9 and 13 s (19.5 % to 21.6 %). Temporal dynamics have been explored using various target presentation methods. Liang et al. (2022) applied the simultaneous-sequential paradigm (Eriksen & Spencer, 1969), where targets are either tracked simultaneously or in subsets while others remain static. For two targets, the sequential condition improved accuracy and reaction times. With four targets, simultaneous tracking performed better, indicating multi-focus attention. At six targets, the sequential condition again yielded better results, suggesting that simultaneous tracking exceeded attentional capacity.

These findings suggest that optimal tracking strategies vary by target count: a single focus suffices for two targets, distributed attention is used for four, and resource limitations force a return to single-focus strategies for six. The results highlight the interplay between working memory and dynamic spatial attention. Managing more targets relies on executive functions like shifting, updating, and inhibition (as defined by Miyake, e.g., (Friedman & Miyake, 2017)), emphasizing the role of high-level cognitive processes in MOT performance.

2.5. Beyond the parameter triad

Specific perceptual characteristics of MOT stimuli such as their spatial configuration, their visual aspects, have also elicited studies. Differences in perceptual features, such as color, shape, or size, improve MOT by helping distinguish targets from distractors. These effects involve both low-level perceptual grouping and higher-level working memory processes.

2.6. Spatial configuration of MOT stimuli

Yantis (1992) suggested that the visual system groups targets into **higher-order representations** to track multiple moving objects efficiently. This process involves two stages: **pre-attentive group formation,** guided by Gestalt principles, and **intentional group maintenance,** requiring focused attention. **Gestalt laws,** such as common fate, simplify complex scenes into coherent shapes, while group maintenance relies on cognitive processes like **mental rotation** and **controlled attention** to update object positions. Fehd and Seiffert (2010) found that observers often focus on an object group's **invisible centroid**, improving tracking by reducing the need to monitor each object individually. Perceptual grouping factors, such as **common fate** and initial configurations, also affect performance, with complex transformations impairing tracking. Objects that **reappear at their last position** are tracked more effectively than those that reappear at predicted locations. Conversely, **Suganuma and Yokosawa (2006)** showed that synchronized target-distractor movements impair MOT performance. Their study found that tracking was **more accurate** when objects moved **independently** (random condition) than when they moved in **close proximity** (chasing condition) or in **coordinated offsets** (trail condition), emphasizing the disruptive effect of synchronized trajectories.

Complementarily, studies show that perceptual grouping based on **featural differences** enhance tracking. When targets and distractors differ in **color** or **shape**, participants perform better than when all objects are identical. Notably, this improvement persists even when distinct features **disappear 1–2 s before the report phase** (Erlikhman et al., 2013), demonstrating the role of **Gestalt principles** like **similarity** in tracking. In addition to grouping by similarity, perceptual grouping by common fate—where co-moving objects are perceived as a group—supports MOT performance. This aligns with Yantis' (1992) work on attentional capture, showing that featural differences guide attention in dynamic tracking tasks.

Depth is another spatial feature that influences MOT, particularly when objects move across varying depth planes. While depth perception involves more complex image processing mechanisms compared to luminance or chromaticity, stereo correlation — that is, the matching of visual information from both eyes to extract depth cues — occurs before higher-level cognitive stages (Faubert & Sidebottom, 2012). Although initially considered cognitively demanding (Faubert & Sidebottom, 2012), studies have shown that tracking 3D objects across different depth planes is easier than tracking on a single plane in 2D (Cooke et al., 2017; Dünser & Mancero, 2009; Viswanathan & Mingolla, 2002). The added depth information in 3D appears to aid object discrimination, improving tracking performance. In particular, stereo depth cues help disambiguate occlusions from object crossovers, facilitating attentional tracking (Faubert & Allard, 2013). However, the 3D advantage over 2D is modulated by the shape of the reference frame, particularly at high object speeds (G. Liu et al., 2005). These findings highlight the interplay between spatial features and movement dynamics in shaping MOT performance.

2.7. Spacing

In MOT**, spacing** refers to the minimum distance between objects. Tracking becomes harder when **targets and distractors are close**, due to **crowding,** which makes isolating individual elements difficult. **Bouma's Law** suggests that crowding reduces when objects are spaced more than half the distance from the center of vision (Bouma, 1970), though this effect is less pronounced in the **visual periphery** (Gurnsey et al., 2011).

2.8. Attention resolution

Beyond crowding effects, **spatial resolution** varies across the visual field and shapes attentional performance. He et al. (1997) found that spatial resolution is finer in the **lower visual field** compared to the upper. In MOT tasks, **Alvarez and Cavanagh (2005)** demonstrated that tracking accuracy drops when **four targets** are confined to a **single hemifield,** but remains stable when targets are **distributed across both hemifields**. This suggests **hemifield independence**, where each **visual**

hemifield processes attention separately: the **left hemisphere** tracks the **right hemifield**, and vice versa (Alvarez & Cavanagh, 2005; Delvenne, 2005). These results indicate that attentional capacity is tied to **fixed spatial zones** in the brain.

2.9. Item uniqueness

Item uniqueness—where each object has distinct features—further enhances MOT, even without perceptual grouping. **Makovski and Jiang** (2009) found that **tracking improved** when items varied in ***shape*** **and** ***color*,** despite becoming identical before the report phase, suggesting a role for **working memory**. Liu et al. (2012) showed that **simple shapes** are easier to track than **complex stimuli,** such as **multidigit numbers** or **Chinese characters,** due to visual working memory's **limited capacity** to maintain detailed identity-location bindings. Interestingly, **Zhao et al.** (2020) found that **item uniqueness benefits** persist even when features **change during motion,** reflecting the **flexibility** of the visual system in updating representations. However, certain **features**, like **line orientation** or **contrast polarity**, are less effective at distinguishing targets from distractors, suggesting that **feature utility** depends on both **feature type** and **tracking demands** (Zhao et al., 2020).

2.10. Unique Identity (MOT) to Multiple Identity Tracking (MIT)

Building on MOT research, **MIT** extends traditional tasks by requiring the simultaneous tracking of **object identity and location,** engaging additional processes like **feature registration** and **memory updating**. **Oksama and Hyönä** (2008) introduced MIT, where participants track both **familiar objects** (e.g., coats or lobsters) and **pseudo-objects** (unfamiliar items). Their **Model of Multiple Identity Tracking (MOMIT)** explains how **serial attention shifts, episodic memory**, and **long-term memory** influence tracking. Their findings show that **performance declines** with increasing **set size** and **object speed**, but familiar objects are easier to track than pseudo-objects. Further experiments confirmed that **familiar faces** are tracked more accurately than **pseudo-faces** ("Frankenstein"), emphasizing the role of **semantic memory** in dynamic tracking (Oksama & Hyönä, 2008). Unlike traditional MOT, MIT requires **linking object identities** to locations, often involving **eye movements** and **sequential attention shifts** (Corbetta & Shulman, 1998). This makes MIT relevant for **real-world tasks**, such as **air traffic control** or **surveillance**, where distinguishing and tracking multiple objects is critical. The **Object-File Theory** (Kahneman et al., 1992) provides a framework for understanding how the visual system maintains **temporary memory representations** that link an object's **location** to its **features** and **identity**. While **object files** are anchored to **spatiotemporal properties,** their **limited capacity** creates challenges in MIT tasks, where both **location** and **identity** must be tracked in parallel.

3. Differential approach of MOT performance

To discover the cognitive mechanisms of MOT, the differential methods proceed analogies by studying MOT in light of its relationships with other non-MOT tasks tapping on specific functions (perceptual, attention, memory, executive functions), or of its impairments in individuals exhibiting differences in specific cognitive functions as for voluntary attention functions in conditions of Attention Deficit Hyperactivity Disorders (ADHD). While these studies suggest that MOT mainly measures dynamic attentional allocation, they do not exclude potential broader training effects. Emerging evidence demonstrates that MOT training can influence ecologically-relevant functions beyond laboratory measures. Specifically, Michaels et al. (2022, 2023) established that 3D-MOT training enhances Useful Field of View (UFOV) performance - a validated predictor of driving competence (Michaels et al., 2022, 2023). This suggests that the visuospatial mechanisms engaged during MOT training may partially generalize to complex real-world demands, while still primarily reflecting core attentional processes.

3.1. MOT Explained by Cognitive functions

Few studies have examined how different attentional paradigms relate within the context of the MOT task (Adolphe et al., 2022; Eayrs & Lavie, 2018; Huang et al., 2012; Skogsberg et al., 2015; Treviño et al., 2021).

3.2. Perceptual grouping

Eayrs and Lavie (2018) explored perceptual capacity using tasks like change blindness, load-induced blindness, MOT, and subitizing (counting items in parallel). Results showed a shared perceptual limit across these tasks: individuals who could quickly count more items demonstrated better performance in detecting changes and peripheral stimuli. Factor analysis revealed a high correlation between MOT and perceptual processing (0.61) and a moderate correlation with working memory (0.40), suggesting that perceptual load plays a critical role in MOT performance.

3.3. Selective attention

Huang et al. (2012) tested 257 individuals on MOT and various attention tasks, finding strong correlations (0.5–0.7) between MOT performance and tasks involving selective attention, such as conjunction visual search, spatial configuration search, enumeration span, rapid color identification, symmetry detection, reaction time, and short-term visual memory. However, weaker correlations were observed for Raven's intelligence test and tasks involving interference control, such as the Stroop task. While these results suggest that MOT performance shares links with visuospatial selective attention-related processes, recent findings indicate that this relationship may be influenced by additional factors. In particular, Tullo, Faubert, and Bertone (2018) demonstrated that the number of targets tracked in MOT is associated with different types of intelligence, such as fluid intelligence, suggesting a more complex interplay between attentional and cognitive processes.

3.4. Perceptual grouping and Divided Attention

Adolphe et al. (2022) developed an open-source cognitive battery comprising tasks such as MOT, enumeration, working memory, and task-switching. Their findings reinforced links between MOT and working memory, aligning with previous studies (Allen, 2006; Lapierre et al., 2017). The study also highlighted connections between MOT and perceptual grouping (i.e., measured with enumeration task, (Green & Bavelier, 2006) as well as the divided attention (i.e., probed by load-induced blindness, (Eayrs & Lavie, 2018).

3.5. Speed processing, perceptual grouping, multiple attention, and working memory

Treviño et al. (2021) further investigated attention-related processes by examining a "general attention factor" in 636 participants using a combination of experimental tasks (e.g., MOT, Visual Working Memory-VWM, Flanker Interference) and neuropsychological tests (e.g., Digit Symbol Coding, Spatial Span, Trail Making Test). Exploratory factor analysis identified five factors: (1) attentional capacity, (2) search, (3) digit span, (4) arithmetic, and (5) sustained attention. MOT clustered within the attentional capacity factor alongside VWM and Approximate Number Sense, as well as Digit Symbol Coding and Spatial Span, highlighting links between tracking, working memory, perceptual grouping, processing speed short-term spatial memory, respectively.

3.6. MOT Explained by cognitive impairments

The MOT task has also been applied in conditions where attention might be impaired or deficient shedding light on the cognitive mechanisms involved in the task.

3.7. Dynamic attentional allocation

Research involving young, non-neurotypical populations, such as children with ADHD, highlights further nuances of MOT-related attentional processes. **Neuroimaging studies suggest that intact MOT performance in ADHD may stem from preserved function in the dorsal attention network (parietal and occipital regions), which supports dynamic visuospatial tracking, despite deficits in fronto-striatal circuits critical for sustained attention** (Hart et al., 2013; Howe et al., 2009)**.** Stubbert (2016) examined how ADHD-related deficits in sustaining and dividing attention might manifest during MOT tasks, employing a dynamic variant of the task designed to reflect real-world demands (Stubbert, 2016). The study included children with ADHD and typically developing children who were matched for age and gender. Results suggested that, despite behavioral attention challenges, the ADHD group performed comparably to controls on MOT tasks. **This dissociation is supported by EEG evidence showing typical alpha/gamma oscillatory activity (linked to visual processing) during MOT in ADHD, contrasting with reduced theta oscillations (associated with executive control) during sustained attention tasks** (Skogsberg et al., 2015)**.** This finding aligns with Fortenbaugh et al. (2015), whose large-scale study of sustained attention demonstrated that it is a distinct cognitive mechanism from the dynamic allocation processes required by MOT. These insights suggest that while MOT tasks effectively measure dynamic attentional allocation, they may not fully capture deficits in voluntary sustained attention.

3.8. Selective attention and spatial updating

When considering other populations with attentional challenges, such as dyslexic individuals, perceptual characteristics in MOT tasks also play a critical role (Franceschini et al., 2012). Dyslexia is associated with visuospatial deficits, which are fundamental for MOT performance. Adjustments to spatial layout and crowding effects in these tasks could offer further insights into the cognitive mechanisms of selective attention and spatial updating in this population, particularly given their reliance on executive functions. These results emphasize the need to tailor MOT tasks to account for the specific cognitive challenges faced by different populations.

3.9. Speed processing and multiple attention

In populations with neurological disorders, a study by Alnawmasi and Khuu (2022) investigated how mild Traumatic Brain Injury (mTBI) affects the ability to allocate and maintain visual attention on multiple moving targets (Alnawmasi & Khuu, 2022). Using an MOT task, the study compared sensitivity—the rate of correct target detection accounting for both hits and false alarms—and reaction times under varying conditions of target number, distractor dots, and tracking durations. The study included 15 adults with mTBI and 20 age-, gender-, and IQ-matched controls. The findings revealed that mTBI patients exhibited significantly lower sensitivity and slower reaction times compared to controls across all conditions, with certain impairments being especially pronounced. Increasing the number of targets reduced tracking accuracy for both groups, but the decline was significantly steeper for the mTBI group, suggesting reduced maximum attentional capacity. Additionally, as tracking duration increased, the performance gap widened, with the mTBI group showing a marked decline in sustained visual attention. The effects of distractor dots further underscored the vulnerability of the mTBI group; their sensitivity decreased more drastically than that of controls, indicating deficits in selective attention and a heightened sensitivity to crowding. Such findings highlight the interplay between attentional capacity, distraction, selective, divided and sustained focus in MOT performance, particularly when cognitive resources are limited due to neurological impairments. In related-way, Bowers et al. (2011) found links between poor MOT performance and worse outcomes on a standardized driving test among older adults. Interestingly, a complementary follow-up study (Bowers et al., 2013) involving 47 participants aged 58–95 found that the UFOV subtest was a far stronger predictor of driving performance than MOT, with the latter failing to provide additional predictive utility (A. R. Bowers et al., 2013). As a result, MOT is seen as primarily assessing divided attention allocation rather than the broader suite of attentional and cognitive skills required for tasks like driving.

3.10. Dimensions of voluntary attention

Skogsberg et al. (2015) investigated the structure of voluntary visual attention and examined potential deficits in individuals exhibiting ADHD traits. The study assessed 529 psychology students from Northwestern University (average age: 18.78 years), among whom 22 females and 13 males were identified as having ADHD traits, based on criteria outlined by Barkley and Murphy (2006). Participants completed 11 visual attention tasks, including MOT, spatial vigilance, rapid reengagement, and object-based shifting. The findings revealed two primary dimensions of visual attention: (1) spatiotemporal attention, encompassing MOT and spatial shifting, contrasted with global attention, which involved object-based shifting and attentional grouping; and (2) transient attention, such as rapid reengagement, contrasted with sustained attention, including spatial and object vigilance. Notably, MOT was strongly associated with spatiotemporal attention but showed weaker associations with sustained attention, underscoring its role in isolating specific attentional mechanisms. Participants with elevated ADHD traits performed within the normal range on most tasks in the attention battery, diverging from previous studies that reported deficits in vigilance and attentional blink tasks among formally diagnosed ADHD patients. This discrepancy likely reflects differences in the populations studied, with the current research focusing on college students with subclinical ADHD traits rather than clinically diagnosed individuals. However, specific deficits were observed in maintaining central focus while inhibiting peripheral distractors. Participants with ADHD traits displayed impairments in suppressing peripheral stimuli, despite showing no deficits in peripheral focusing, indicating that the impairment was not due to a general issue with response inhibition but rather to difficulties in managing peripheral distractions. These behavioral findings align with neuroimaging evidence pointing to abnormalities in brain regions involved in selective attention and distractor inhibition (Hart et al., 2013). Nevertheless, the relatively small sample size of participants with ADHD traits limits the strength of the conclusions drawn from this study.

3.11. Summary

Analytical studies demonstrate that attentional tracking in MOT tasks is influenced by multiple interacting factors, particularly through the manipulation of MOT parameters (Table 1). Since Pylyshyn and Storm's (1988) pioneering work, researchers have debated whether tracking relies on discrete resource slots or a flexible, continuous pool. By altering MOT parameters, three key evidence-based conclusions have emerged: (1) Performance declines as speed, target number, or tracking duration increases, aligning with discrete resource theories; (2) Studies on spacing and trajectories reveal that crowding disrupts tracking. Notably, Holcombe and Chen (2013) found that raising target numbers or speeds degrades performance even without spatial interference, suggesting finite resources limit tracking capacity; (3) Theories diverge on whether tracking involves a single attentional spotlight or multifocal

Table 1
Overview of MOT task parameters and their outcomes.

Parameter	Values	Observed performances	Cognitive function	Theoretical model
Object number	8 objects (3 or 4 targets) (Pylyshyn, 2001; Pylyshyn & Storm, 1988) 2,4,6 objects (Oksama & Hyönä, 2008) 1 to 8 targets (Alvarez & Franconeri, 2007)	Increasing the number of targets almost always reduces performance.	Attention Dynamics: Constraint of available resources with periodic attentional effort. Focused attention Selective attention	FINST Visual spatial indexes (Pylyshyn & Storm, 1988): Limited number of objects in the visual field FLEX Model (Alvarez & Franconeri, 2007)
Object speed	0°/s to 42°/s (Alvarez & Franconeri, 2007) 0.06 cm/s to 544 cm/s (Tullo, Faubert, & Bertone, 2018)	Performance decreases as speed increases and increases as speed decreases. Speed reduces performance by demanding the hemisphere-specific resource (Chen et al., 2013), whereas VSTM is for the most part not hemisphere-specific. Resource demands of object tracking and differential allocation of the resource.	Visual short-term memory Focused attention	FLEX Model (Alvarez & Franconeri, 2007) Tracking capacity governed by a continuous pool of resources (Bettencourt & Somers, 2009)
Tracking duration	5, 9, 13 s (Oksama & Hyönä, 2008)	Tracking performance over time: performance declines from 5 to 9 s (error percentage increases firm 9.0 % to 19.5 %). Same performance (plateau effect) from 9 to 13 s (error percentage ranges from 19.5 % to 21.6 %). Difficulty maintaining attention on multiple objects over extended periods.	Flexible functions of working memory and dynamic spatial visual attention (<5 s). As the number of targets increases, reliance on high-level, non-automatic processes tied to executive functions grows (>5 s): shifting, updating and inhibition	MOT theory comparison: (Oksama & Hyönä, 2008) findings contradict (Pylyshyn & Storm, 1988) pre-attentive view, which posits that tracking duration does not affect MOT performance
Perceptual characteristics				
Spacing	Spacing between objects (Franconeri et al., 2010; A. Holcombe, 2023)	Impact of Object Proximity: The closeness of objects has a deleterious impact, known as crowding	NA	Finite tracking resources are constrained by both spatial and temporal factors (A. Holcombe, 2023)
Trajectory	Randomized to prevent overlap with each other or frame Speeds tested: 0.5 s, 1 s, 2 s 3 s, 4 s (Suganuma & Yokosawa, 2006)	Trajectory Modifications and Tracking Performance: Alterations in tracking ability when target and distractors pursue each other or move uniformly. Better performance when objects reappear at their last known position rather than a new location based on prior movement	Working memory and controlled attention for tracking.	Grouping Theory (Yantis, 1992) Common movements serve as cues for forming global object representations (Suganuma & Yokosawa, 2006) to emphasize the role of motion cues in enhancing group perception
Object appearance	Shape, color, characters. Warming: not their absolute appearance except for VanMarle and Scholl (2003) with fluid-like texture.	Item Uniqueness. Performance improved when all items differed in shape and color, despite becoming identical before the report phase (Makovski & Jiang, 2009)	Semantic memory: general knowledge about familiar objects; Episodic memory: Recollects specific events, experiences with familiar objects (MIT, (Oksama & Hyönä, 2008).	Simultaneous allocation of attention to multiple locations or objects within the visual field (Alvarez & Cavanagh, 2005; Z. W. Pylyshyn, 2001)

attention (Fig. 2). For example, Liang et al. (2022) and Oksama and Hyönä (2008) demonstrate that tracking strategies adapt to target numbers and required attentional precision. Complementing this, differential psychology research supports the idea that MOT engages complex visuospatial mechanisms interacting with broader cognitive functions—including selective, sustained, and divided attention, working memory, executive control, and even real-world activities like driving (Table 1). However, findings in children with ADHD highlight limitations in using MOT tasks to assess impaired sustained attention. Overall, evidence suggests that parameter manipulation dynamically shapes attention allocation for efficient target tracking, solidifying MOT's potential for CT and safety-critical applications (Vater et al., 2021).

Numerous studies in visual and attentional research have employed the cognitively multi- determined MOT task:

- The FINST Model's pioneering concept (Z. Pylyshyn, 1994) identified MOT as a process potentially guided by **pre-attentive stimuli**, using a mechanism that tracks multiple objects without detailed attention or conscious recognition. The brain assigns visual spatial indexes to a limited number of objects in the visual field.
- The Grouping Theory (Yantis, 1992) sheds light on the visual system's capacity to simplify tracking by **unitizing individual targets into a cohesive visual entity.**
- The FLEX Model (Alvarez & Franconeri, 2007) introduced the idea of a **malleable pool of attentional resources that adjusts dynamically to the demands of tracking complexity**.
- While earlier theories like the **Spatial Interference Theory** (Franconeri et al., 2010) emphasized spacing-related limits, the field has since shown that **both spatial crowding** (studied extensively in visual psychophysics) and **temporal frequency** constrain MOT performance. This highlights the need to consider the combined impact of spatial and temporal interferences rather than relying on single-factor explanations.
- The Holcombe and Chen (2013)'s work underscored the limitations of tracking resources, countering the notion that spatial interference alone affects tracking accuracy.
- The Multifocal Attention Theory (Cavanagh & Alvarez, 2005) explored the possibility that multiple attentional beams can be directed toward **different objects simultaneously**, enhancing the understanding of how attention is distributed in MOT tasks.
- The correlation-based studies (typical and non-neurotypical individual-differences approach) revealed a strong to moderate bond with the visual processing, **dynamic attention**, **selective**, **sustained** and **divided** attention, as well as with **working memory**.

These influential models face important limitations: The FINST account struggles to explain performance degradation with increasing targets (Oksama & Hyönä, 2004); cf. (Scholl, 2009), while the FLEX model's resource continuity conflicts with observed discrete capacity limits (A. O. Holcombe & Chen, 2013; Vater et al., 2021). Multifocal theories, though accounting for distributed tracking, remain challenged by evidence of serial attentional shifts (Liang et al., 2022). Overall, MOT does not tap a monolithic cognitive function but a complex dynamic interplay of visual processing, attentional resources, and working memory, shaped by both the intrinsic properties of the objects being tracked and the overarching conditions of the task.

4. Laboratory (task related) Outcomes from MOT Practices

Q2. How does MOT-based CT influence task performance (near-transfer effects)? Does changing task parameters modulate these effects? How does MOT practice impact cognitive functioning (from near to far transfer), in both neurotypical and non-neurotypical conditions?

While it is unequivocal that performance on almost any cognitive task can be improved with training, many major questions remain. These include the extent to which improvements generalize—or transfer—to untrained cognitive tasks and contexts, how this degree of transfer varies across cognitive domains, what characteristics of training interventions facilitate or hinder generalization, and how pre-existing individual differences influence outcomes. Traditionally, CT literature distinguishes the *near* and the *far transfer* effects to assess the degree of generalization.

4.1. Near Transfer Effects of MOT Training and role of MOT parameters

MOT training consistently leads to significant performance gains in tasks that are closely related to the trained activity, a phenomenon referred to as ***near-transfer***.

4.2. In neurotypical participants

Repeated practice on MOT tasks enhances **tracking performance**, particularly in terms of **speed thresholds, attentional capacity**, and **visuospatial processing** (Harris et al., 2020; Musteata et al., 2019; Parsons et al., 2016; Tullo, Faubert, & Bertone, 2018). The majority of studies have focused on **3D-MOT paradigms**, often utilizing **NeuroTracker** (Box 2) to measure these improvements. For example, Parsons et al. (2016) implemented a **3D-MOT training protocol** with 20 university students (aged 18–25), dividing them into a training group and a non-active control group. After ten sessions, each lasting between 45 and 60 min over five weeks, the training group exhibited significant **tracking speed improvements** compared to controls. Similarly, Harris et al. (2020) evaluated **84 young adults** across four groups (untrained controls, standard NeuroTracker, abbreviated NeuroTracker, and portable NeuroTracker) and found robust improvements across all training conditions ($\boldsymbol{p < 0.001}$). Importantly, older adults also benefit from MOT training. **Musteata et al. (2019)** conducted a 14-session program with participants aged 60–75 years, including individuals with and without **subjective cognitive decline**. Both subgroups demonstrated **significant gains in tracking speed thresholds**, indicating that MOT training is effective across age groups.

Manipulating key parameters of the MOT task—such as **increasing speed thresholds** or **the number of targets**—appears **essential** for enhancing **CT efficacy**. Most studies have manipulated between **two and four targets** during training sessions (e.g., (Faubert, 2013; Howe et al., 2009). As seen before, **increasing the number of targets** could potentially stimulate **more flexible cognitive functions,** such as **executive processes** (e.g., **updating** and **working memory**). For example, **Parsons et al. (2016)** emphasize the concept of **overloading**, where participants are pushed beyond their current capacity to induce **cognitive adaptation**. Yet, very few studies have systematically explored the effects of modifying **other task parameters**, such as **spatial layout**, **distractor proximity**, or **stimulus complexity**—despite theoretical evidence suggesting that these factors can **significantly influence cognitive performance** (cf. Q1). This limited exploration of task parameters restricts our understanding of how different manipulations might optimize training outcomes. Although NeuroTracker represents a methodological advance in 3D-MOT research by combining standardized protocols with parametric flexibility, most studies have employed its speed-threshold paradigm for comparability. Consequently, the platform's capacity for parameter modification (e.g., target-distractor ratios, display characteristics) remains underutilized in investigating training efficacy. **More critically, this methodological narrowness may obscure potential interactions between parameters that could prove crucial for enhancing far-transfer effects to real-world cognitive demands.**

4.3. In non-neurotypical conditions

Near-transfer effects have been observed as well (Tullo, Bertone, et al., 2018) adapted a standard protocol for students with **autism spectrum disorder (ASD)** and **ADHD** by reducing the number of targets to three. The study compared an active training group with a visual strategy-based control group and a treament-as-usual group. After **15 sessions** over five weeks, the intervention group showed a **41 % improvement** in speed thresholds ($\boldsymbol{p < 0.001}$), underscoring the

Box 2: Common experimental design with NeuroTracker task training

3D-MOT or Neurotracker

Multiple studies on MOT as a training task used either the commercial NeuroTracker tool or a variant of the 3D-MOT. To give readers an overview of usual experimental designs, we selected four articles that were prominently featured on the NeuroTracker website (https://www.neurotrackerx.com/scientific studies) to illustrate typical experimental protocol (Faubert, 2013; Musteata et al., 2019; Parsons et al., 2016; Romeas et al., 2016)

Apparatus

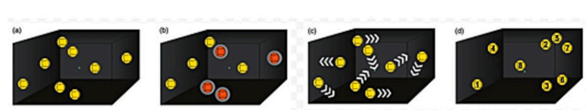
Participants either stands or sits inside or in front of an augmented reality environment with a virtual scene projected on the frontal and sometimes lateral walls (for instance the EON IcubeTM, a 7x10x10 feet room Romeas et al., 2016 or a CAVE a 8x8x8 feet room Legault and Faubert, 2012). The task is practiced between 1 and 2 meters from the frontal display Legault and Faubert, 2012 with stereoscopy generated by the use of active shutter glasses (for instance the CrytalEyes 4s (RealD) (Romeas et al., 2016)).

Task

In the CORE mode of Neurotracker, participants usually have to track 4 targets (colored in red) among 4 distractors (in yellow). After an initial presentation of object (typically around 2s) (a), an indexing phase lasts around 1 second where targets are highlighted with a halo (b). Then, objects move linearly in the 3D space without occlusion for 8s (c). Objects are indexed with numbers and participants have to verbally recall the number of targets initially presented (d). Training sessions are typically structured in several blocks of 20 trials Parsons et al., 2016 or 8 minutes. Complete training last around 15 sessions separated by break days Faubert, 2013.

Difficulty adjustment and performance estimation

Difficulty is adjusted through a 1up-1down procedure on speed. Staircase steps are usually set to 0.05log. After each block, staircases are reset and performance on the session is computed as the mean of the final state of all staircases.



Neurotracker protocol, image taken from Romeas et al., 2016

Box 2. Common experimental design with NeuroTracker task training.

flexibility of MOT training for diverse populations. Once again, the paucity of studies on the impact of MOT parameters' manipulations impedes reliable conclusions about the specific cognitive mechanism enhanced with MOT practices and its near cognitive transfers.

Overall, most studies indicate that **performance gains** occur regardless of the **training program's duration,** suggesting that improvements in tracking abilities can emerge from **short- or long-term protocols**. Unfortunately, it remains difficult to insight precisely which enhanced cognitive mechanisms by MOT training due to a nonsystematic investigation of MOT parameters 'manipulations as provided by analytical approaches of MOT.

4.4. *Open-ended issues*

It raises critical question on the setup of MOT for training purpose. **What is the optimal number of sessions required for effective cognitive training?** According to **Von Bastian and Oberauer (2013)**, the literature remains **inconsistent** regarding session duration and its impact on **transfer effects.** Unfortunately, more than a decade later, this inconsistency persists. Another key consideration concerns the **structure of the MOT task** itself. For instance, **NeuroTracker** typically requires participants to track **four red targets** among **four yellow distractors** (Box 2). But what happens when we modify **other parameters**? Variations in the **number of targets**, **distractors,** or even the **complexity of movement trajectories** may also influence the **effectiveness of training**, yet these aspects remain **underexplored** in the literature. Addressing these gaps could offer a **more comprehensive understanding** of how different **MOT task configurations** affect **cognitive performance improvements**. Further research is needed to clarify **which task parameters** promote **broader near cognitive benefits**.

4.5. *3D-MOT or NeuroTracker*

Multiple studies on MOT as a training task used either the commercial NeuroTracker tool or a variant of the 3D-MOT. To give readers an overview of usual experimental designs, we selected four articles that were prominently featured on the NeuroTracker website (https://www.neurotrackerx.com/scientific studies) to illustrate typical experimental protocol (Faubert, 2013; Musteata et al., 2019; Parsons et al., 2016; Romeas et al., 2016).

4.5.1. *Apparatus*

Participants either stands or sits inside or in front of an augmented reality environment with a virtual scene projected on the frontal and sometimes lateral walls (for instance the EON IcubeTM, a 7x10x10 feet room Romeas et al., 2016 or a CAVE a 8x8x8 feet room Legault & Faubert, 2012). The task is practiced between 1 and 2 m from the frontal display Legault & Faubert, 2012 with stereoscopy generated by the use of active shutter glasses (for instance the CrytalEyes 4 s (RealD) (Romeas et al., 2016)).

4.5.2. *Task*

In the CORE mode of Neurotracker, participants usually have to track 4 targets (colored in red) among 4 distractors (in yellow). After an initial presentation of object (typically around 2 s) (a), an indexing phase lasts around 1 s where targets are highlighted with a halo (b). Then, objects move linearly in the 3D space without occlusion for 8 s (c). Objects are indexed with numbers and participants have to verbally recall the number of targets initially presented (d). Training sessions are typically structured in several blocks of 20 trials Parsons et al., 2016 or 8 min. Complete training last around 15 sessions separated by break days Faubert, 2013.

4.6. *Difficulty adjustment and performance estimation*

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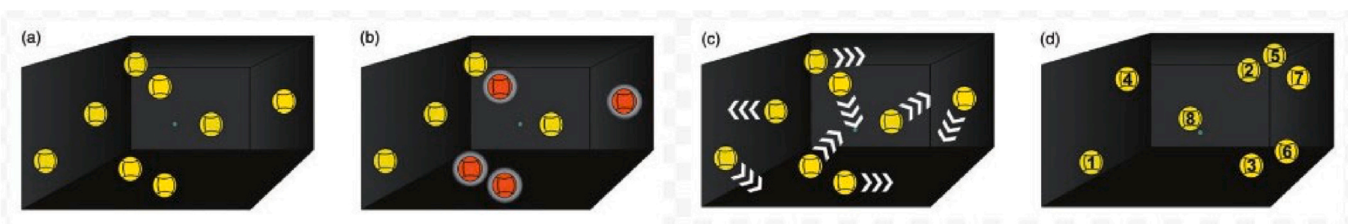

Neurotracker protocol, image taken from Romeas et al., 2016.

5. Far Transfer Effects of MOT Training and Influence of MOT parameters

Another critical question in CT research is whether the benefits of MOT training extend beyond near-transfer effects to broader, more distinct tasks, referred to as *far transfer*. Following an individual difference approach, these effects involve improvements in cognitive domains unrelated to the training, such as episodic memory, executive functions. The effects can be estimated in correlation with neuropsychological tests mostly interconnected with the trained tasks. However, empirical evidence for far transfer remains inconsistent, due to **divergent operational definitions and methodological heterogeneity across studies.**

5.1. *In neurotypical participants*

Harris et al. (2020) assessed far transfer in 84 young adults using route recall and audio monitoring tasks but found no significant improvements. Strong and Alvarez (2017) tested far-transfer effects in university students (aged 18–25) using tasks with varying motion types and retinotopic locations. Despite including an active visual search task as a control, the study found no evidence of far transfer. **Musteata et al. (2019)** evaluated far-transfer effects in older adults using tasks assessing episodic memory (e.g., abstract word recall) and cognitive flexibility (e.g., verbal fluency). While significant gains were observed immediately after 14 sessions of 3D-MOT training, these effects were not sustained at follow-up.

5.2. *In non-neurotypical participants*

Far-transfer effects seems to have shown more promise in non-neurotypical populations (Tullo, Bertone, et al., 2018) found improvements in executive functions, such as cognitive flexibility, in children with ASD and ADHD (aged 6–18 years) using neuropsychological tools like the CPT-3 (Tullo, Bertone, et al., 2018). This study included both a passive control group and an active control group trained on a math-strategy game, strengthening the validity of its findings. In individuals with low vision (LV), Nyquist et al. (2016) implemented a dual-task MOT paradigm targeting both central and peripheral attention. Participants underwent 10 training sessions involving either a modified Multi-Attentional Tracking (MAT) task, conventional AVGs, or a non-action video game (control). Significant far-transfer effects were observed in peripheral motion discrimination and spatial crowding tolerance, with gains sustained 12 months post-training. These findings underscore the potential of MOT training to address attentional deficits in specialized populations. Similarly, **Bertoni et al. (2019)** studied dyslexic children (aged 8–12 years), finding enhancements in reading speed, selective attention, and reduced visual crowding after training. These more consistent far-transfer effects in clinical populations may stem from their baseline deficits being more directly aligned with MOT's core demands (e.g., attentional control in ADHD, visual crowding reduction in dyslexia). However, these effects are difficult to generalize, as non-neurotypical individuals often present specific cognitive profiles and may respond differently to the same task. This makes it challenging to extend the results to other populations.

5.3. Open-ended issues

Even if the reported far-transfer effects are encouraging, they remain fraught with conceptual and methodological challenges. **A core issue is the lack of consensus in defining far transfer: while some studies classify attention-adjacent improvements (e.g., UFOV, Attentional Blink) as far transfer** (Joessel, 2022)**, others consider them near transfer (Vater et al.,** 2021**). This inconsistency reflects MOT's dual nature - it can be framed either as a specific attentional task or as a broader cognitive training tool.** Moreover, far-transfer assessments often rely on heterogeneous, non-standardized tasks (e.g., episodic memory, decision-making) that lack clear theoretical links to MOT, making it difficult to distinguish true transfer effects from task-specific learning. If near transfer is reliably assessed using MOT analogs for pre- and post-intervention measures, far transfer is assessed through different non-MOT tasks that are more or less truly far of MOT with strong differences across the studies yielding inconsistencies in findings. For instance, Joessel (2022) investigated the cognitive benefits of action video games (AVGs) through a feasibility study involving 263 online participants. After 12 h of training on one of four game variants incorporating dual-task MOT elements, participants were evaluated using a cognitive assessment battery that included tasks targeting various cognitive domains. The MOT task was used to assess near transfer, while far-transfer effects were measured through tasks such as: (1) the UFOV task for spatial attentional control, (2) the Attentional Blink task for temporal attentional control, (3) a Corsi task for short-term memory, and (4) the N-back task for working memory. The study found significant improvements for MOT task for participants who trained with AVGs, demonstrating cognitive transfer beyond the initial training task. By contrast in their review, Vater et al. (2021) **discussed how** improvements in attention, situational awareness, executive functions, working memory, and processing speed **can be categorized** as near-transfer effects whereas far-transfer effects are expected on more complex cognitive processes like decision-making. The tasks selection for assessing transfer effects is actually influenced by the conceptual vision of MOT. Focusing on MOT as primary training of attention, some studies focus on near and far attention-specific effects, where improvements are closely tied to the trained MOT task (e.g., working memory, UFOV), while others implement MOT training as global attention allocation training (involving multiple cognitive functions such as attention, working memory and executive functions) that aim to enhance broader cognitively effortful capabilities. Such a distinction raises further concerns about the interpretation of CT effects, as noted by Sala and Gobet (2019).

Furthermore, other methodological limitations hinder conclusions about far-transfer effects. A common limitation is the use of passive control groups, which fail to account for motivational or expectancy effects. Participants in passive control groups may simply lack the engagement or challenge provided by the intervention, which can inflate the perceived benefits of training (Boot et al., 2013). Attrition in multi-session protocols is another concern, as dropouts can introduce bias into results, yet few studies address this issue or account for it in their analyses (McCarney et al., 2007). Another pervasive issue is the reliance on small sample sizes, particularly in studies involving clinical populations. Small samples reduce the statistical power of studies and increase the risk of Type II errors (Cohen, 2016; Simmons et al., 2011). Addressing these methodological gaps through more rigorous designs, larger samples, and more comprehensive parameter manipulations could provide deeper insights into the true potential of MOT training to produce far-transfer effects.

6. Real-Life (task-related) Outcomes from MOT Practices

Q3. What real-world transfer effects arise from MOT training in neurotypical individuals, and how do non-neurotypical conditions modify these effects?

A critical question beyond the existence of transfer effects is how and why MOT tasks might enhance real-world skills, such as decision-making or performing complex tasks under pressure. Several theoretical frameworks help explain this process. One such framework is the Primitive Information Processing Elements (PRIMs) Theory proposed by Taatgen (2013), which suggests that individuals can reuse previously learned cognitive elements when acquiring new skills. If two tasks share PRIMs, positive transfer is more likely to occur. The greater the overlap, the stronger the transfer—a phenomenon similar to near transfer. In other words, near transfer fosters efficient knowledge-based strategies for performing a task, either through overlearned rules or compiled knowledge. PRIMs theory further suggests that far transfer is possible if tasks involve shared executive functions, particularly those related to cognitive control. For instance, practicing a complex working memory task can improve Stroop task performance, as both rely on proactive control (Braver et al., 2007). In this case, we refer to resource allocation or executive strategies that optimize task performance. It is worth noting that knowledge-based transfer strategies enhance information-processing efficiency, freeing up cognitive resources that can then be allocated to other mechanisms that improve performance. This aligns with Wickens' Multiple Resource Model (2002), which suggests that cognitive improvements result from better processing efficiency rather than direct skill transfer (Wickens, 2008). In other words, MOT training primarily optimizes how individuals allocate cognitive resources, reducing mental load during complex tasks.

6.1. In neurotypical Individuals

Derived from PRIMs, the Cognitive Routine Framework by Gathercole et al. (2019) assumes that repeated exposure to cognitive routines during MOT tasks can lead to process automation, reducing cognitive load and improving performance on complex real-life tasks (Gathercole et al., 2019). As a result, MOT training may enhance the brain's efficiency in managing cognitive resources, particularly in dynamic and fast-paced environments. A practical example of this connection is seen in sports. Athletes in sports such as soccer or volleyball must perform quick situational analyses, make rapid decisions, sustain attention, and continuously update their mental representations—all cognitive functions engaged during MOT tasks. Romeas et al. (2016) demonstrated this in their study on soccer players, showing that 3D-MOT training led to significant improvements in passing accuracy and decision-making on the field, while control groups did not show similar gains. This finding suggests that repeated MOT practice may cognitively automatize procedural tasks like dribbling or passing, thereby reducing cognitive load and improving performance under pressure. Further evidence is provided by Fleddermann et al. (2019), who integrated 3D-MOT training with volleyball-specific drills. After an eight-week program, players showed improved performance in near-transfer tasks (e.g., sustained attention, processing speed), but no evidence of far-transfer effects on volleyball-specific skills like blocking or spiking. Interestingly, the study highlighted the risk of cognitive overload in dual-task scenarios. Players demonstrated reduced jumping efficiency when simultaneously processing complex visual stimuli. Therefore, promising effects of MOT training are reported on decision-making for some complex naturalistic activities such as sport. **However, these improvements often prove transient, highlighting a critical limitation in sustaining far-transfer effects. The ephemeral nature of benefits may stem from insufficient training duration to induce neuroplastic changes, lack of periodic reinforcement sessions, or fundamental mismatches between laboratory MOT tasks and real-world demands. Parameter adjustments could address these limitations - for instance, enhancing ecological validity through sport-specific stimuli (e.g., player avatars instead of abstract objects), implementing progressive difficulty scaling that adapts to individual progression, or developing hybrid protocols that combine MOT with domain-specific drills (Che et al., 2023; Fleddermann et al., 2019).**

Beyond sports, research suggests that MOT tasks engage cognitive mechanisms essential for everyday activities, particularly for mobility and safety in aging populations. Legault and Faubert (2012) investigated this by examining the impact of 3D-MOT training on older adults' ability to perceive Biological Motion (BM)—the recognition of human movement patterns from point-light displays. BM perception is crucial for identifying pedestrians and assessing balance, both of which are vital for maintaining mobility and preventing falls. The study found that only the 3D-MOT group showed significant improvements in BM perception after training, suggesting that MOT can enhance older adults' ability to process socially relevant visual information, potentially reducing fall risk. Green and Bavelier (2008) explored this idea in the context of everyday multitasking and adaptability. Their work focused on how targeted cognitive training—such as action video games requiring rapid visual tracking and attentional shifts—can enhance general cognitive flexibility. They argued that such training does not merely improve task-specific skills but fosters **cognitive adaptability** by simulating the demands of real-world environments (e.g., driving, navigating crowded spaces, or multitasking at work). To test this, they conducted longitudinal training studies comparing action video game players to non-players, measuring transfer effects to tasks like multiple-object tracking, attentional blink, and spatial resolution. Their results showed that action gamers outperformed controls not only on trained tasks but also on untrained tasks requiring rapid decision-making and dynamic attention allocation. Critically, they emphasized that improvements depended on **learning progression** (e.g., adapting to increasing difficulty levels) rather than repetitive practice alone, suggesting that MOT training must challenge users in ecologically valid ways to promote real-world transfer. This assumption posits that MOT training does not simply enhance performance on specific tasks but could also strengthen flexible cognitive processes, such as attentional control and working memory updating, which are critical across diverse real-life scenarios. Such an assumption is supported by an aging study revealing that older adults exhibited greater cognitive declines in dual-task scenarios of MOT, indicating reduced flexibility and procedural efficiency compared to younger participants (Pothier et al., 2015). **For aging populations, effect sustainability faces additional challenges from neurobiological constraints. The dual-task MOT performance declines observed by Pothier et al. (2015) suggest older adults may require optimized parameters (e.g., slower initial speeds, extended target durations) for effective skill acquisition. Furthermore, maintenance protocols like monthly refresher sessions or multi-modal approaches combining MOT with physical exercise might yield more durable effects given age-related cognitive reserve limitations.**

6.2. In non-neurotypical individuals

Children with Developmental Dyslexia (DD) provide a compelling example of how the effects of MOT training vary across diverse populations. Bertoni et al. (2019) explored this by using action video games (AVGs) that share core features with MOT tasks, such as fast object tracking and perceptual-motor demands. The training aimed to improve visual-spatial attention, which is often impaired in children with DD. After 12 h of AVG training, children showed significant gains in visual-spatial attention and reduced visual confusion, leading to improved reading speed without a loss in accuracy. While these improvements are likely linked to better processing speed, the evidence for transfer to broader academic skills remains limited. Notably, the study emphasized the importance of active engagement, as improvements were only observed in children who actively participated in training. This highlights the importance of effortful processing for effective cognitive interventions in neurodiverse populations.

6.3. Open-ended issues

Direct evidence of long-term real-world improvements remains scarce, raising questions about the ecological validity of MOT-based interventions. **The frequent lack of sustained far-transfer effects appears rooted in three key challenges: insufficient training duration to induce neuroplastic change, over-reliance on abstract stimuli that limit real-world generalization, and absence of maintenance protocols to preserve gains.** Additionally, their cognitive cost-effectiveness—in relation to both the extent and sustainability of cognitive outcomes—remains largely unexplored. Existing studies do not address this issue. **Parameter adjustments may offer solutions: ecologically valid adaptations (e.g., sport-specific visuals instead of spheres), progressive difficulty scaling aligned with real-world demands, and hybrid formats combining MOT with domain-specific practice could enhance effect durability, as suggested by Fleddermann et al.'s (2019) mixed results with volleyball players.** Furthermore, the lack of systematic investigation into how MOT parameters influence real-life outcomes limits our ability to identify the transfer mechanisms, particularly in terms of knowledge-based strategies and cognitive resource allocation. **Future research should prioritize parametric studies to optimize training protocols, longitudinal designs to track effect decay, and multimodal approaches that bridge laboratory training with real-world contexts.** This gap makes it difficult to assess their actual impact on everyday activities.

7. Conclusion

This review provides a synthesis of current research on MOT training, emphasizing its potential transfer effects across both neurotypical and non-neurotypical populations. By identifying key gaps and offering actionable recommendations, it seeks to advance the understanding and practical application of MOT in diverse domains. Unlike previous reviews that have primarily focused on narrow methodological perspectives or specific populations, this work adopts a broader, application-oriented approach, emphasizing the flexibility of MOT task parameters and their potential for cognitive enhancement in education, sports, and healthcare.

Research on MOT training spans a wide range of populations, from children (Bertoni et al., 2019) to older adults (Legault & Faubert, 2012) and individuals with attentional or executive disorders. The adaptability of MOT tasks is further evidenced by their application in fields such as sports, where meta-analytic evidence confirms performance advantages for athletes (Fleddermann et al., 2019; H. J. Liu et al., 2024). The modular nature of MOT parameters—such as the number of distractors, target speed, or task complexity—makes it a valuable tool for investigating how cognitive mechanisms interact with clinical profiles. For example, adjusting cognitive load during MOT tasks offers unique insights into visual and attentional processing in populations with conditions such as dyslexia or attention disorders.

Despite its promise, the integration of MOT training into broader CT programs remains in its early stages. Many studies focus on dual-task paradigms that combine MOT with other tasks—such as the UFOV or motor-based exercises—to better simulate real-world scenarios. However, these studies often lack comprehensive neuropsychological assessments, limiting our understanding of the underlying cognitive mechanisms that drive training effects (A. Bowers et al., 2011; Fleddermann et al., 2019). While some correlations have been observed between MOT-based attentional paradigms and improvements in executive functions, memory, and attentional control (Adolphe et al., 2022; Eayrs & Lavie, 2018; Huang et al., 2012; Treviño et al., 2021), inconsistencies in assessment tools raise concerns about the validity and reproducibility of these findings (Vater et al., 2021; Von Bastian & Oberauer, 2013). This lack of consistency is further compounded by the absence of studies that systematically examine more than one parameter with a rigorous focus on their interactive or combined effects.

8. Future directions

A major limitation in current MOT-based CT research is its dependence on rigid, standardized protocols. Most programs use a "one-size-fits-all" approach, advancing participants at a fixed pace regardless of their starting abilities. This risk widening the gap between high and low performers, as those with weaker baseline skills, gain fewer benefits. Studies like Joessel (2022) and Nyquist et al. (2016) advocate for personalized interventions that adapt difficulty in real-time based on performance. **While foundational studies established core MOT mechanisms** (Alvarez & Franconeri, 2007; Wickens, 2008)**, emerging work demonstrates the importance of contemporary parameter optimization approaches** (Föcker et al., 2022; Knobel et al., 2022), including the development and evaluation of AI-based personalization algorithms for attention training (Adolphe, 2024). Customizing task parameters to individual needs keeps challenges optimal, maximizing training effectiveness (Anderson, 2018). **Future studies should test whether adaptive algorithms that adjust speed, the number of distractor, and target proximity based on real-time performance (1) reduce dropout rates in low-performing participants and (2) yield more uniform skill acquisition across ability levels. We hypothesize that such systems will particularly benefit clinical populations with attention deficits when using threshold-based progression models.** Addressing this variability is key to improving MOT-based CT's inclusivity and impact. **Critically, future research must move beyond isolated parameter manipulations to investigate how combinations of parameters (e.g., high speed and high target load) impose nonlinear cognitive demands.** For instance, while increasing speed alone may tax temporal attention, coupling it with elevated distractor density could overwhelm spatial filtering capacities, creating synergistic bottlenecks predicted by **multiple-resource theory** (Wickens, 2008). **Systematic factorial designs (e.g., 2 × 2 manipulations of speed and target number) paired with pupillometry or EEG could quantify whether these interactions deplete shared or distinct cognitive resources, refining models of attentional resource allocation (Alvarez & Franconeri, 2007).** Such work would clarify whether MOT training efficacy hinges on optimizing single parameters or balancing trade-offs between them—a key consideration for personalized protocols.

Similarly, participant engagement and motivation during MOT training are often neglected. In fields like education and healthcare—where long-term adherence matters—task design must consider how complexity and feedback systems affect intrinsic motivation. Research highlights cognitive progress itself as a motivator (Oudeyer et al., 2016). For example, Moen et al. (2018) stress the need for tasks that stay engaging over time to sustain participation (Moen et al., 2018). Future work should explore how adjusting MOT parameters influences motivation and test strategies like gamification or adaptive feedback to boost involvement. **To move beyond generic proposals, testable hypotheses could frame gamification research: (1) Narrative feedback systems (e.g., framing MOT tasks as "rescuing targets in a story mission") are predicted to increase intrinsic motivation compared to points-based systems, measurable via the *Intrinsic Motivation Inventory* (Ryan & Deci, 2000) and time-on-task metrics; (2) Variable-ratio reward schedules (e.g., unpredictable bonus trials) are hypothesized to sustain engagement longer than fixed schedules, leveraging operant conditioning principles (Skinner, 1961) and quantifiable through weekly retention rates; (3) Avatar customization options (e.g., personalized visual traits) are expected to enhance identity attachment (Banks & Bowman, 2016), improving adherence in multi-session paradigms when compared to non-customizable interfaces.**

Looking ahead, a key question that remains unresolved is which cognitive mechanism primarily drives the efficacy of MOT training (H. J. Liu et al., 2024). Is it the automation of attentional processes—such as faster visual grouping and enhanced processing speed—or the development of executive strategies, such as improved cognitive flexibility and task coordination? Understanding which mechanism predominates will be critical for refining training protocols and tailoring them to specific populations. For example, if the primary benefit comes from attentional automation, MOT training could be most effective in populations with attentional deficits. In contrast, if executive strategies are the primary driver, MOT training might be more suited to populations that struggle with multitasking or task-switching. Here, too, careful examination of parameter manipulations is likely to be useful in view of the fundamental findings on the parameter triad and beyond. To determine whether MOT training benefits stem primarily from automated attention or improved executive control, future studies should employ two complementary approaches: First, neuroimaging protocols could compare the development of early visual attention markers (like **N2pc components**, which reflect automatic tracking of spatial attention) (Luck & Hillyard, 1994) versus frontal lobe activation patterns (like **theta oscillations** in the prefrontal cortex, which index executive effort during cognitive control) (Jensen & Tesche, 2002). Second, comparative intervention studies could examine whether populations with distinct cognitive profiles—such as **ADHD** (primarily executive dysfunction; (Barkley, 1997) versus **dyslexia** (mainly sensory-attention deficits) (Facoetti et al., 2010)-show systematically different improvement patterns when exposed to identical MOT parameter modifications. **This dual approach aligns with frameworks emphasizing dissociable neural substrates for automatic and controlled attention** (Posner & Petersen, 1990) **and could clarify whether MOT efficacy depends on domain-general executive mechanisms or domain-specific attentional tuning.**

Finally, the issue of ecological validity remains a pressing challenge. To ensure that the benefits of MOT training translate to real-world scenarios, future research must incorporate task complexities that mirror everyday environments more accurately. Studies by Ericson and Beck (2013) and Lochner and Trick (2014) highlight the importance of including unpredictable distractors, dynamic trajectories, and context-dependent task goals to better replicate real-life cognitive demands (Ericson & Beck, 2013; Lochner & Trick, 2014). **Recent advances in immersive technologies** (Knobel et al., 2022) **and multimodal cueing** (Föcker et al., 2022) **offer promising avenues to enhance ecological validity while maintaining experimental control.** Enhancing the ecological validity of MOT tasks will not only improve their practical relevance but also provide more robust insights into how cognitive training generalizes across contexts. **Rather than generic ecological improvements, future work could evaluate: (1) context-specific MOT variants (e.g., classroom-relevant distractors for educational applications), (2) the impact of multimodal stimuli (auditory and visual targets) on transfer to real-world tasks** (Föcker et al., 2022)**, and (3) whether environment-embedded training (e.g., Augmented Reality /Virtual Reality simulations** (Che et al., 2023)**) enhances far-transfer compared to laboratory tasks** (Knobel et al., 2022)**. Ericson and Beck's (2013) findings suggest that unpredictable distractors may need domain-specific tailoring to maximize relevance.**

By addressing these methodological and conceptual gaps, researchers can unlock the full potential of MOT training as a versatile tool for cognitive enhancement. This endeavor will deepen our understanding of attentional and executive processes, facilitate the broader integration of MOT into CT paradigms, and promote its real-world application across domains such as education, sports performance, clinical rehabilitation, and occupational training.

CRediT authorship contribution statement

Pech Marion: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Adolphe Maxime:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Oudeyer Pierre-Yves:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Conceptualization. **Sauzéon Hélène:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Consent to participate

Not Applicable.

Consent for publication

All authors have approved the manuscript and consent to its submission for publication. The research has not been presented at any prior conferences or workshops.

Ethics approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Code availability

Not applicable.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

No data was used for the research described in the article.

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