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**Angaben zur Veröffentlichung / Publication details:**

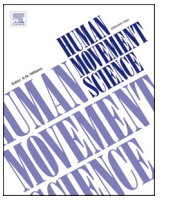
Beißel, Patrick, Tobias Huber, Martin Nowak, Elisabeth André, and Stefan Künzell. 2026. "Choosing difficulty: self-determined versus assigned tasks in motor sequence learning." *Human Movement Science* 107: 103483. https://doi.org/10.1016/j.humov.2026.103483.

Human Movement Science 107 (2026) 103483

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov



Full Length Article

# Choosing difficulty: Self-determined versus assigned tasks in motor sequence learning

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ARTICLE INFO

*Keywords:*
OPTIMAL theory
Autonomy support
Sequence learning
SRT task
Implicit motor learning
Complex task
Task integration

ABSTRACT

The OPTIMAL theory of motor learning, from its introduction to its subsequent refinement, has catalyzed a substantial body of research into motivational effects on motor learning with both supportive evidence and critical debate. This paper examines the effects of goal-directed practice, provided either through autonomy-supportive practice conditions—hypothesized by the OPTIMAL theory to yield motivational benefits—or a yoked group or a low-autonomy instructor, on implicit motor sequence learning of a complex, bimanual dual task. Participants practiced a motor sequence in a virtual reality serial reaction time (SRT) task and were either given or denied control over task difficulty as a task-relevant choice. While all groups successfully acquired the target sequence, differences between groups were negligibly small or absent altogether. These results suggest that the motivational effects of autonomy support do not substantially impact the motor learning of complex tasks.

## 1. Introduction

In current motor learning research, the OPTIMAL (Optimizing Performance Through Intrinsic Motivation and Attention for Learning) theory by Wulf and Lewthwaite (2016) (Wulf & Lewthwaite, 2021) has caused a surge in subsequent studies aimed at examining its claims of improving motor learning and performance through motivational and attentional factors (St. Germain et al., 2023). The OPTIMAL theory is a successor of two prominent; earlier theories: firstly the self-determination theory; itself a conglomeration of the Basic Psychological Needs theory; the Cognitive Evaluation theory and the Organismic Integration theory (Sanli, Patterson, Bray, & Lee, 2012); which states that motivation results from having one's basic psychological needs (competence; autonomy; and relatedness) met (Deci & Ryan, 2000; Parma, Miller, & Bacelar, 2024; Ryan & Deci, 2000). Secondly, the ideomotor theory, that supposes that actions are represented by their intended effects (Greenwald, 1970; Hommel, Müsseler, Aschersleben, & Prinz, 2001; James, 1890). Since these effects are normally observed in the external environment, G. Wulf, Höß, and Prinz (1998)

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https://doi.org/10.1016/j.humov.2026.103483
Received 30 October 2025; Received in revised form 18 March 2026; Accepted 24 March 2026
Available online 1 April 2026

developed the hypothesis that directing attention to external events enables better motor control and learning than directing attention to internal processes of the own body. Building on these theories; the OPTIMAL theory proposes three key factors that can positively influence motor processes (Wulf & Lewthwaite, 2016, 2021):

- Enhanced Expectancies: learners' self-efficacy expectations towards future tasks, driven by past success or other beneficial task conditions.
- External Focus: directing attention towards the intended movement effect instead of the movement itself.
- Autonomy Support: providing learners with a sense of control over their learning process, often by offering choices.

These key factors may independently and interactively contribute to improved goal-action coupling, priming the motor system for subsequent actions, and lead to an increase in motivation (Parma et al., 2024; Phillips, Hodge, Myers, Leventhal, & Burgess, 2024; Simmonds, Wakefield, Coyles, & Roberts, 2023; Simpson, Cronin, Ellison, Carnegie, & Marchant, 2020; Wulf & Lewthwaite, 2016, 2021). Increased motivation is theorized to influence the consolidation of procedural memories and goal directed movements, yet the precise mechanisms and effects on motor learning remain unclear (Parma et al., 2024; Phillips et al., 2024; Wulf & Lewthwaite, 2016). The key factors' effects are active during and after practice and may result in improved motor performance and learning (Leiker, Pathania, Miller, & Lohse, 2019; Parma et al., 2024; Simmonds et al., 2023). The main motivational variable of interest in this study is autonomy support, as it is a factor strongly influenced by coaching style (Mageau & Vallerand, 2003; Mouratidis, Lens, & Vansteenkiste, 2010). A coach's performance-oriented practice can strongly affect an athlete's perceived autonomy and be beneficial or detrimental to the learning process (Goffena & Horn, 2021; Schröder, 2024; Sigrist, Rauter, Riener, & Wolf, 2013).

To provide autonomy support, learners can be provided with a sense of self-control over practice conditions which, according to the OPTIMAL theory, will enhance motor performance and learning. The opportunity of choice is often instrumental in this regard, as choices are beneficial for intrinsic motivation and feelings of competency (Parma et al., 2024; Patall, Cooper, & Robinson, 2008; Patall, Sylvester, & Han, 2014). There have been many studies assessing the influence of task-relevant and task-irrelevant choices in this context (Shooli, Saemi, Boushehri, Seifourian, & Simpson, 2024; Simmonds et al., 2023). More recent research argues that both categories of choice create rewarding conditions and a distinction is therefore not necessarily warranted (Shooli et al., 2024; Simpson et al., 2020), while there are nevertheless studies that argue for a clearer distinction (Carter & Ste-Marie, 2017; St. Germain et al., 2023). Practice variables that participants are usually given choice over include different forms of feedback modes, movement demonstrations, the amount and order of practice repetitions, use of assistive devices, and many task-irrelevant choices, such as choosing the color of materials used in experiments (Chiviacowsky, Borges Martins, & Cardozo, 2021; Sigrist et al., 2013; Wulf et al., 2018; Wulf & Lewthwaite, 2016). All of these variables can help tailor practice conditions to learners' needs and consequently enhance motivation as postulated in the OPTIMAL theory (Sigrist et al., 2013; Wulf & Lewthwaite, 2021). There are contrasting opinions, however, which explain the advantages of self-determined practice from a cognitivist, information-processing perspective (McKay & Ste-Marie, 2022). Self-controlled learning can engage learners more deeply in a task; facilitate cognitive processing; and allow for performance contingent switching to an ideal task difficulty in accordance with the challenge point framework (Andrieux, Boutin, & Thon, 2016; Guadagnoli & Lee, 2004; Pathania, Leiker, Euler, Miller, & Lohse, 2019; Pollok et al., 2022; Quan, Wang, Wang, & Kang, 2024; Sertic, Avedesian, & Navalta, 2021). Ultimately, attempting to separate motivational and information-processing effects is difficult and may be redundant, as autonomy might affect motivation through its effect on information processing (McKay & Ste-Marie, 2020; Pathania et al., 2019; Simpson et al., 2020). To summarize: the OPTIMAL theory postulates autonomy support as one of three motivational factors that can influence motor learning through motivational or information-processing effects or both. Autonomy support can be provided by offering task-relevant or task-irrelevant choices.

The OPTIMAL theory has, however, also received criticism in recent years. While several studies found positive effects of enhanced expectancies, external focus or autonomy support on motor performance, the claim of beneficial combinatory effects (Wulf, Chiviacowsky, & Drews, 2015; Wulf, Lewthwaite, Cardozo, & Chiviacowsky, 2018) remains to be conclusively proven (Shooli et al., 2024; Simpson et al., 2020). There are also several studies that found no significant or very minor effects on motor processes (McKay & Ste-Marie, 2020, 2022; Parma et al., 2024; Quan et al., 2024; St. Germain et al., 2023), despite some reporting differences in perceived autonomy and motivation (McKay & Ste-Marie, 2020; Parma et al., 2024). A review study by Parma et al. (2024) looked at 166 studies using enhanced expectancies or autonomy support as variable and concluded that only eight studies found group-level effects on motivation; while only five studies reported positive effects on motor learning. McKay, Bacelar, Parma, Miller, and Carter (2023) also published a meta-analysis of 73 articles on self-determined practice and enhanced expectancies; noting that motor learning benefits were likely exaggerated due to reporting bias and underpowered study designs. According to these papers; the performance difference between self-determined 'choice' and externally controlled 'yoke' groups overall seems to be small or even non-existent. This lack of clarity in results regarding the motor performance effects of the OPTIMAL theory calls for more research into these processes. Pertaining to this; new studies have been conducted in the field of motor sequence learning; assessing among other factors the effects of reward; voluntary choice; feedback; cooperation or competition (Lewis et al., 2022; Quan et al., 2024; Si, Wang, & Kawczyński, 2025). The resulting impact on intrinsic and extrinsic motivation was shown to affect performance in the Serial Reaction Time Task (SRTT) and its variations (Anderson, Lohse, Lopes, & Williams, 2021; Bonassi et al., 2023; Gamble, Lee, Howard, & Howard, 2014; Si et al., 2025; Wong, Lindquist, Haith, & Krakauer, 2015), for both implicitly- (Barth, Stahl, & Haider, 2024; Quan et al., 2024; Schumacher & Hazeltine, 2016) and explicitly-trained skills which likely operate in parallel (Anderson, Adkins, Gary, & Lee, 2020; Dyck & Klaes, 2024; Hadjiosif & Krakauer, 2021; Maresch, Mudrik, & Donchin, 2021; Moisello et al., 2009; Schumacher & Schwarb, 2009). To which extent motivation affects sequence learning is, however, still unclear, as Quan et al. (2024) found that opportunity for task-irrelevant choice significantly affected sequence learning in a simple SRTT; yet not retention. Therefore; given the recent criticism of studies on

motivational effects on motor learning (McKay et al., 2023; Parma et al., 2024), more research on sequential tasks needs to be done, especially using complex motor tasks. Prior research has largely focused on simple motor tasks (Beißel & Künzell, 2024, 2025; Levac, Huber, & Sternad, 2019); while complex ones have only been used incidentally (e.g. Khalaji, Nezakat Alhosseini, Safavi Hamami, Iwatsuki, & Wulf, 2024) rather than as an explicit focus of investigation. This paper aims to add to this discussion by assessing the effects of autonomy support on sequential motor learning of complex tasks and contrasting it with the effects of low-autonomy; yet instructor-guided practice conditions. As the field's focus on elementary motor tasks and their limited transferability to realistic tasks has been criticized in the past (Beißel & Künzell, 2024; Sternad, Huber, & Kuznetsov, 2014; Zhao, Zhang, & Xu, 2024), this study will follow Levac et al.'s (2019) definition of complex tasks as having nested redundancy: a complex task exhibits more execution variables than task-defining variables – across intrinsic, extrinsic and task redundancy – and thus allows for a multitude of effector positions, movement trajectories and target solutions to perform the task.

In this context of motivational influences on motor (sequence) learning, the interplay of goal-directed behavior—whether self-initiated or facilitated by an instructor— and autonomy support warrants closer examination. Goal-directed behavior is the foundation of effective motor learning and can be initiated and maintained through learners' motivation, as well as through resulting mechanisms such as focused attention (Wong et al., 2015). A coach or instructor inherently provides similar goal-directed behavior; as they aim to assist their protégés in reaching a predefined goal (Grant, 2019). Able coaches will be aware of their potentially great impact on motivation; which can be influenced by the degree of autonomy support provided to their learners (Mageau & Vallerand, 2003; Mouratidis et al., 2010). By incorporating the learners' decisions and opinions into planning subsequent practice units, coaches can increase persistence and well-being (Mouratidis et al., 2010). It can also aid in providing a suitable level of challenge to the learner by balancing nominal and functional task difficulty (Andrieux et al., 2016; Guadagnoli & Lee, 2004; Simmonds et al., 2023). Yet coaches' efforts can likewise produce inadequate practice conditions. While a more goal-directed coaching style can be more effective than a person-centered one, the feeling of being regulated externally may incur high emotional costs and negatively impact desired goals (Grant, 2019; Mouratidis et al., 2010). The same holds true for unwanted, improper or insincere feedback (Mouratidis et al., 2010). To disentangle the effects of goal-directed practice conditions from additional motivational effects, this study implements the established choice condition which can autonomously influence their practice progression and a yoke condition which is matched to the progression of the choice group. These conditions are contrasted with a 'motivationally neutral' trainer group that provides goal-directed practice conditions with adequate difficulty progression, yet without offering autonomy support.

Choice over task difficulty during the practice phase was used as motivational, task-relevant variable to provide or withhold autonomy support. Research on the motivational and information-processing effects of difficulty as an autonomy variable has yet received limited scholarly attention (Akizuki & Ohashi, 2015; Bright, Smith, Kearney, & Runswick, 2025; Wadden, Hodges, de Asis, Neva, & Boyd, 2019) and current evidence remains inconclusive: some studies on difficulty-based autonomy effects show improved performance of self-controlled choice groups over yoked groups which can be attributed to ideal cognitive and motivational engagement (Andrieux et al., 2016; Leiker et al., 2016; Leiker et al., 2019; Pathania et al., 2019; Westlin, Day, & Hughes, 2019). Others report higher intrinsic motivation and engagement for choice groups, yet with no significant effects on learning (Leiker et al., 2016; Leiker et al., 2019). Clearly separating the potential causal effects of increased motivation from information-processing effects remains a further challenge in this line of research (Bright et al., 2025; Leiker et al., 2016; Leiker et al., 2019; Ste-Marie, Carter, Law, Vertes, & Smith, 2016). Likewise, different degrees of autonomy will have to be assessed as well, as Andrieux et al. (2016) have shown that partially autonomous groups' learning may outperform fully autonomous groups.

A recent study by Bright et al. (2025) has assessed several of the mentioned aspects; using difficulty manipulation in a simple task as motivational variable; by testing for differences in intrinsic motivation; learning; and cognitive effort between performance contingent; fixed difficulty; autonomous; and yoked groups. While successful learning; retention and transfer could be shown through increased task accuracy; along with high cognitive effort and decreased motivation; no significant group differences were found. In line with the more recent; critical literature on the OPTIMAL theory (McKay et al., 2023; McKay & Ste-Marie, 2020, 2022; Parma et al., 2024; Quan et al., 2024; St. Germain et al., 2023), the authors concluded that positive learning effects mediated through autonomy or performance contingent difficulty changes may be minimal and even suppressed when task difficulty is high (Bright et al., 2025).

The findings of this and other studies using task difficulty manipulation as an autonomy variable indicate a lack of consistent evidence on the effects of autonomy on learning success. A similar pattern of results can be found in the wider literature on autonomy support. While task difficulty is clearly distinct from commonly used choice over feedback modalities, results are still comparable, as both variables appear to affect shared underlying processes and both are usually adjusted by learners dependent on trial outcomes, the relative amount of practice or due to strategic reasons (Pathania et al., 2019). Furthermore; even though a high degree of learner autonomy may well result in increased motivation and deeper involvement in the task; learners may still create adverse learning environments through preference-performance dissociation (Ziv & Lidor, 2021). This effect is usually mediated through a trainer which may negatively affect autonomy (Mageau & Vallerand, 2003; Mouratidis et al., 2010). Yet one could argue that receiving goal-directed practice conditions by a coach reduces the need for self-regulation which might lead to less stressful practice conditions (Pathania et al., 2019). This would in turn benefit automatic control mechanisms and benefit implicit learning (Simmonds et al., 2023; van der Veer, Bastiaenen, Rameckers, & Klingels, 2024). Trying to reach a higher difficulty level when it is controlled externally may also increase motivation, especially for more competitive learners (Gamble et al., 2014; Si et al., 2025).

To summarize: while prior research has generally supported the positive motor learning effects proposed by the OPTIMAL theory, more recent reviews and experimental studies have questioned whether motivational factors substantially affect objectively measurable learning success. Within autonomy research, empirical data on difficulty manipulation as a motivational variable is scarce and inconclusive. Moreover, as in the broader motor learning literature, additional studies on complex and sequential motor skills would benefit this research area. And lastly, the influence of trainer-guided learning, despite its prevalence in learning environments,

remains underinvestigated from both a motivational and information-processing perspective. The aim of this study therefore was to test for measurable performance and learning differences between a choice, yoked and trainer group learning a complex, sequential motor task. Based on the theories discussed here, we examined two hypotheses. First, following the basic tenets of the OPTIMAL theory, we postulated that general performance and sequence learning in a complex motor task would improve for participants provided with autonomy supportive practice conditions compared to a yoked group. The choice over difficulty is highly individual and situational, a lack of autonomy would therefore negatively affect the yoked group's motivation and thus task proficiency. Second, we argue that a trainer group, provided with no autonomy support but goal-directed difficulty progression during practice, would perform equally well or better than a self-determined choice group. Choosing the ideal difficulty during practice requires expertise and experience beyond a novice's self-assessment, which should provide trainer-assisted learners with a significant advantage despite a lack of autonomy support.

## 2. Methods

### 2.1. Participants

Voluntary participants between the age of 18 and 30 were recruited from sports students at the university's sports center. Relevant group size was determined through prior experiments (Beißel & Künzell, 2024, 2025) and a G-Power (Faul, Erdfelder, Lang, & Buchner, 2007) a priori sample size calculation based on the implicit-learning score analysis by Schmidtke and Heuer (1997). Planning a one-way ANOVA with an effect size of $f = 0.56$, an error probability of 0.05., and power = 0.95, group size was set to 17. The 51 participants' mean age was 22,3 (SD = 4,3) years, with 26 female and 25 male participants. Of these, 41 were right-handed, nine were left-handed and one was ambidextrous. Findings of this study should generally be transferable to healthy, non-elderly and non-learning-impaired adults.

### 2.2. Apparatus

A virtual reality (VR) headset and corresponding controllers were used in this VR setup. Participants wore a Valve Index VR headset containing two 1440 × 1600 LCD IPS fast switching displays with refresh rates of 144 Hz and a field of vision of 135°. Each hand was fitted with a controller with 87 sensors for measuring hand positions and applied pressure, as well as an accelerometer for measuring linear acceleration. Movement tracking was provided by two stationary base stations with a Lighthouse 2.0 tracking system, placed in opposing corners of a 6 m × 6 m area. As 'motion-to-photon' latency longer than 90 ms can negatively affect participants' motor performance while using VR systems (Kelkkanen, Lindero, Fiedler, & Zepernick, 2023; Warburton, Mon-Williams, Mushtaq, & Morehead, 2023), maximal latency of 6.9 ms and average latencies of 3.6 ms were measured for this experiment and considered unproblematic. The VR environment was developed using the Unity game engine version 2018.4 (Unity Technologies, 2019). The built-in physics engine was used to simulate physical interactions within the VR system.

### 2.3. Task

A supplemental video can be viewed online (https://rb.gy/zikpx6). We adapted the classic SRT task to a virtual reality environment to be able to implement and measure complex motor tasks. We used a bimanual dual task, as these are comparable to many realistic tasks in everyday life and commonly used in motor learning experiments (Beißel & Künzell, 2024, 2025; Cienfuegos et al., 2024; Haith, Yang, Pakpoor, & Kita, 2022; Schoenfeld, Thom, Williams, Stagg, & Zich, 2024; Yeganeh Doost, Orban de Xivry, Bihin, &

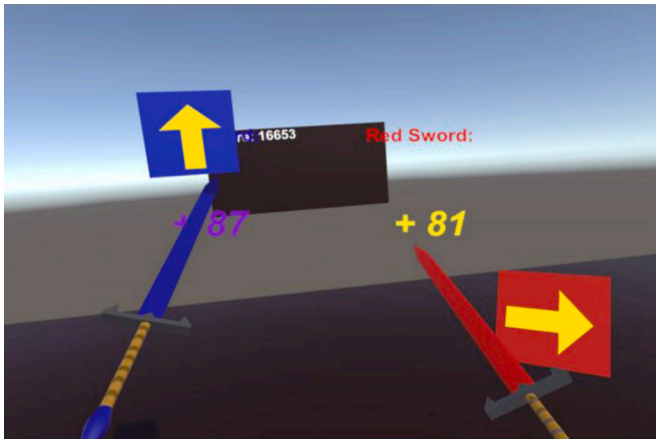


**Fig. 1.** *Experimental Setup*. The bimanual dual task as seen from the participants perspective. Individual hit scores and a background total score provided performance feedback. New stimuli always appeared within the participants field of vision.

Vandermeeren, 2017). While simple bimanual SRT tasks have been used frequently in past research (Berner & Hoffmann, 2008; Bhakuni & Mutha, 2015; Hamano, Sugawara, Yamamoto, Fukunaga, & Sadato, 2024; Schmitz, Pasquali, Cleeremans, & Peigneux, 2013; Trapp, Lepsien, Sehm, Villringer, & Ragert, 2012), complex bimanual SRT tasks remain understudied (Beißel & Künzell, 2024, 2025). Participants wearing the VR headset saw a featureless plane before them, while holding a red and blue sword in their right and left hand, respectively. The task began with a pair consisting of one red and one blue cube appearing within their field of vision. The overall task was a complex, bimanual dual task in which participants were asked to hit through the stimuli on their dominant-hand side (task 1) and non-dominant-side (task 2) with the matching swords as quickly and close to the center as possible. The correct direction for the hit was indicated by predefined directional arrows on the cubes and could be different or identical between cubes (see Fig. 1). Only vertical and horizontal hits were implemented, resulting in four possible directions (up, down, left and right). For each hit, the angle between the actual hit trajectory and the direction specified by the arrow was measured. Hits from the wrong direction or surpassing an angle of 46° were counted as incorrect. Successful hits and mistakes were each accompanied by unobtrusive positive or negative sound effects. After successful completion or a set time frame, the cubes would be replaced by a new pair with no stimulus onset asynchrony. The cubes would appear at similar heights within a predefined offset in front of the participant in a predefined sequence, yet the red cube would always appear to the right of the blue cube and vice versa. With few exceptions during specific phases of the experiment and unbeknownst to the participants, the stimuli for both tasks appeared in predefined, repeating sequences consisting of six cubes. Based on our previous experiments (Beißel & Künzell, 2024, 2025) and to ensure ideal motor sequence learning conditions, both sequences were consistently shown in the same order to allow for task integration processes. While both tasks share the same modality, they are distinct tasks and a form of multitasking. Bimanual tasks have been shown to impose increased complexity, performance limitations, and reduced accuracy and stability on motor learning (Beißel & Künzell, 2024; Hazeltine, Ruthruff, & Remington, 2006; Swinnen & Wenderoth, 2004; Wenderoth, Bock, & Krohn, 2002). This is still more pronounced when hand-specific tasks differ and are performed simultaneously, especially because coordination control mechanisms are initially dominant and cause a delayed development of sequence-specific mechanisms (Yeganeh Doost et al., 2017).

### 2.4. Design

The experiment was conducted over two separate days, with a one-week interval between them. It assessed improvements through practice and learning on day one, as well as performance in a retention and transfer test on day two. Both retention and transfer tests were implemented because previous experiments on motivational effects on motor learning did not necessarily find performance changes during practice but found positive effects on retention and transfer tasks (Iwatsuki & Otten, 2021; Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015; Quan et al., 2024). The time interval between the sessions was adapted from a similar study by Leiker et al. (2016). Response time (RT) in seconds (s), percentage of successful hits (HIT) (%), and precision (PR) (%) were recorded as dependent variables. To assess precision, three segments within each cube (at the front, in the middle, and at the end of the hit direction) determined the average distance of each successful hit to the cube's center, returning an overall precision score. For each segment, the distance to the cube's center was measured in steps of 10% of the distance from the center to the edges of the cube (rounded down). Then we inverted this value such that hits closer to the cube's center yielded higher precision values, whereas hits near the edges returned lower values. For example, if a hit missed the center of the cube by an average 12% of the distance between the center of the cube and its borders, then it was assigned a precision of 100% - 10% = 90%.

From these variables, an implicit learning score (ILS) was calculated in the test phase on day one and the retention test on day 2 (see 2.5) to serve as a measure for learning improvement. The ILS is a common measure for implicit learning in motor studies (Quan et al., 2024; Robertson, 2007; Sense & van Rijn, 2018; Trofimova, Mottaz, Allaman, Chauvigné, & Guggisberg, 2020) which is calculated from the difference in performance between familiar motor sequences and a catch trial consisting of (quasi-) random stimuli. Additionally, a score derived from the RT, HIT, and PR variables and multiplied with the respective difficulty level was implemented as a means of providing feedback for participants. Difficulty levels ranged from 1 (easiest) to 10 (hardest). While it was not used for statistical analysis in this study, these accumulated scores were displayed on a board in the background of the virtual room to indicate to participants whether they were scoring high or low. Each successful hit of a cube also prompted the cube-specific score to briefly appear as a number above the hit cube. Scores were calculated with the formula:

(remaining time to hit (%) x 60 + PR (%) x 60) x difficulty modifier.

The difficulty modifiers increased by 0.3 increments for each difficulty level and ranged from 0.3 to 3.0.

Difficulty adjustment was implemented as task-relevant motivational variable for providing or withholding autonomy support. As in previous studies that used a game-like task to assess the influence of self-controlled practice and motivation (Leiker et al., 2019; Pathania et al., 2019), higher difficulty levels reduced the size of the stimuli and the available time to interact with them. At difficulty level 1, each cube measured 30 cm in diameter and cubes were replaced after 2.75 s if not hit successfully. Cube diameter was reduced by 2.5 cm and available time by 0.25 s for each subsequent increase in difficulty. When transitioning to the highest difficulty 10, the reduction was limited to 1.5 cm and 0.125 s for a final diameter of 8.5 cm and available time of 0.625 s, as exploratory tests found this to be the feasible performance limit for trained participants. Participants therefore had to be faster and more precise on higher difficulty levels, which likely also increased psychological pressure.

### 2.5. Procedure

A schematic of the experiment's procedure is shown in Fig. 2. The experiment began on day one with obtaining informed consent from participants after instructing them, as well as familiarizing them with the equipment and virtual environment. Two tutorial

blocks of cubes on difficulty 1 had to be completed next, each block consisting of 64 stimulus pairs, which repeated all 16 possible hit directions. Break time between blocks was always 30 s, unless noted otherwise. All participants' scores in the second tutorial block were recorded and used as a basis for group assignment. Participants with similarly high scores were matched between groups to ensure homogenous distribution. Participants were reminded to be as fast and precise as possible, next to being informed about their group-specific difficulty adjustment (see 2.6) and the upcoming high-difficulty test phase. The further task structure remained identical for all groups: first a practice phase with varying difficulty levels in accordance with group consisting of eight blocks had to be completed. Each block consisted of the aforementioned parallel sequences of six cubes per hand, repeated ten times; resulting in 60 cube pairs per block. Participants then had a five-minute break before beginning the test phase. The test phase consisted of six blocks identical to the practice blocks, except for blocks three and four, which contained 60 quasi-random cube pairs with no immediate repetitions. The quasi-random sequence was identical for all participants and designed to be similar in difficulty to the practice sequence. Blocks three and four served as a catch trial to calculate the ILS (see 2.4) and thus measure implicit motor sequence learning. The test phase was performed at difficulty level 8, which – through pre-tests and expert consultation - was designed to provoke an error rate of 15–30% for more experienced participants. Previous studies estimate an error rate around 15–30% to be ideal for learning (Akizuki & Ohashi, 2015; Al-Fawakhiri, Kayani, & McDougle, 2023; Wilson, Shenhav, Straccia, & Cohen, 2019). This concluded day one. After exactly one week and after having received a reminder of the upcoming task structure, participants began day two with one tutorial block on the lowest difficulty level to warm up and refocus on the task. They then completed both a transfer and retention test at difficulty 8, the order of which was swapped for half the participants to counterbalance order effects between both tests (Shea & Morgan, 1979). The transfer test consisted of two blocks with the identical sequences used in the practice and test phase, yet with different locations on the horizontal plane. The retention test was identical to the test phase of day one, including the catch trial. The experiment concluded with a short interview to assess the degree of explicit sequence knowledge that was potentially gained during the experiment.

### 2.6. Conditions

Participants were assigned to one of three conditions, Choice, Yoke or Trainer group. Based on the condition, difficulty was adjusted after each block during the practice phase of the experiment. All participants were informed that it would be followed by a test phase on a high difficulty setting. Instructions were given in a fashion similar to prior studies (Wulf, Iwatsuki, et al., 2018; Wulf & Lewthwaite, 2016; Wulf, Lewthwaite, et al., 2018). Choice was given full autonomy over their practice phase and participants were told they were “free to choose” the difficulty of each block. Yoke was informed that difficulty would randomly vary during their practice, with no mention of opportunity for choice. The difficulty changes for participants in the Yoke condition were matched to the choices of their respective counterparts in Choice, e.g. participant #3 in Yoke received the practice progression of participant #3 in Choice. The final condition, Trainer, was also not given any self-control and informed that a trainer would adjust difficulty levels for them. This ensured goal-driven practice, based on individual performance. Trainer started their first practice block at difficulty level 4, “medium”. As a basis for deciding the subsequent difficulty, the percentage of successful hits in each block was then recorded and compared to an ideal error rate of 15%, which was derived from the previously mentioned error-rate studies (Akizuki & Ohashi, 2015; Al-Fawakhiri et al., 2023; Wilson et al., 2019). The difficulty level was then maintained for success rates between 82.5%–87.5% and lowered or increased for every 5% deviation. After the first practice block; difficulty was adjusted fully in accordance with this rule to ensure an adequate starting difficulty. E.g.; if a participant hit only 69% of the cubes; then the difficulty would be decreased by three levels. For subsequent blocks; a maximum difficulty decrease of one level and increase of two levels was implemented to simulate a human coach's efforts to keep training load changes to a sensible level and not overshoot the optimal challenge point (Guadagnoli & Lee, 2004). Based on the predictions of the OPTIMAL theory and our derived hypotheses, we expected Choice to display lower RT and error rates, as well as higher PR and ILS scores compared to Yoke, with similar or superior results for Trainer compared to Choice. This pattern should be found for general performance, sequence learning, and retention / transfer effects.

### 2.7. Data processing and analysis

Relevant data can be accessed online (https://rb.gy/zikpx6). Data was recorded within the Unity VR application and saved in individual .csv files, one for each block of cubes. The variables for all blocks and participants were aggregated into one summary file which was then used for statistical analysis. The variable ‘HIT’ was calculated from the percentage of successful hits to total trials. Means for each block were used to summarize the participants' performance for RT and PR. Hits that were missed or performed incorrectly were excluded for the latter two variables to avoid data dilution or inflation through outliers. The ILSs were calculated for all variables from the day one test phase and day two retention blocks. The mean difference between the quasi-random blocks three and four compared to the familiar blocks two and five was calculated for the ILS scores. The ILS was also used to identify outliers, with exclusion criteria set at more than two standard deviations from the test phase group mean in all variables. Such participants would have been excluded from all analyses, which however was unnecessary as only two participants in Choice and Trainer, and one participant in Yoke deviated significantly in one variable each. Statistical analysis was performed using Jamovi, version 2.3.26 (The jamovi project, 2023). Data sets were checked for normality distribution using Shapiro-Wilk tests and parametric or non-parametric tests were used accordingly. Levene's test was used to test for homogeneity of variance for analyses of variance (ANOVA) and Games-Howell or Tukey post-hoc tests were then used as reported in the results. Assumptions of sphericity were assessed using Mauchly's sphericity test, and the Greenhouse-Geisser correction was applied when assumptions were violated.

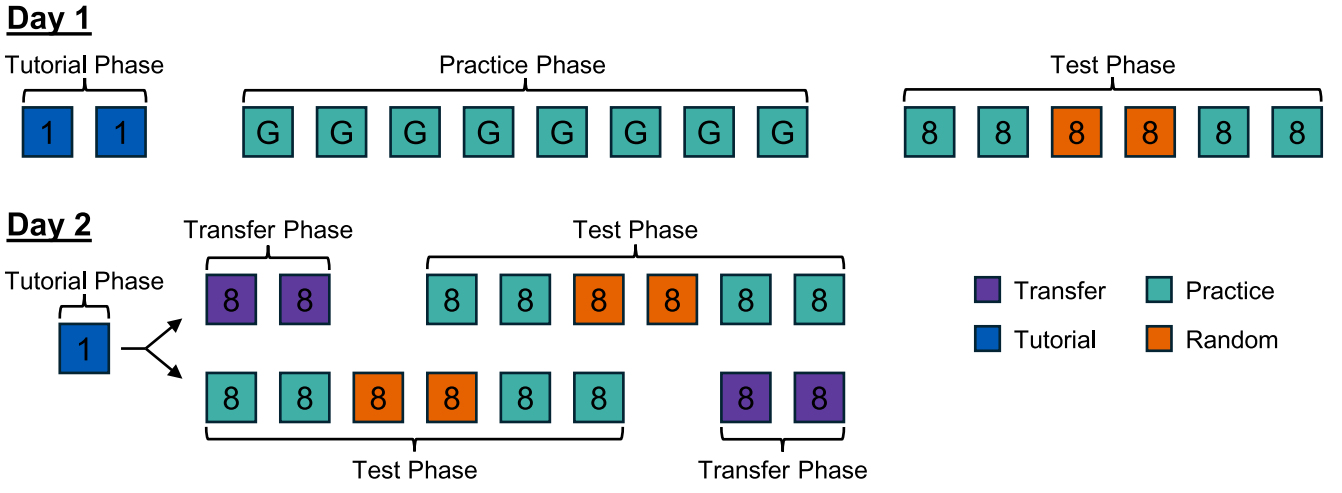


**Fig. 2.** *Protocol Flowchart of the Experiment.* Each square represents a block of 64 (tutorial) or 60 stimulus pairs (all others). The colors indicate which sequence was used in each block. The numbers indicate fixed difficulty levels from 1 to 10 for the respective blocks, the letter 'G indicates the group-specific difficulty adjustment implemented during the practice phase on the first day. On the second day, the order of phases was reversed for half of the participants to counterbalance potential order effects between both tests.

**Table 1**
Baseline Performance Comparison.

| Variable | Choice | | Yoke | | Trainer | | *F* (2,48) | *p* |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | | |
| RT [s] | 0.99 | 0.17 | 1.01 | 0.02 | 0.99 | 0.10 | 0.035 | 0.966 |
| | | | | | | | $\chi^2$ (2) | *p* |
| HIT [%] | 99.7 | 0.67 | 99.2 | 1.95 | 99.7 | 0.56 | 0.487 | 0.784 |
| PR [%] | 69.9 | 9.03 | 68.7 | 9.48 | 66.3 | 13.8 | 0.658 | 0.720 |

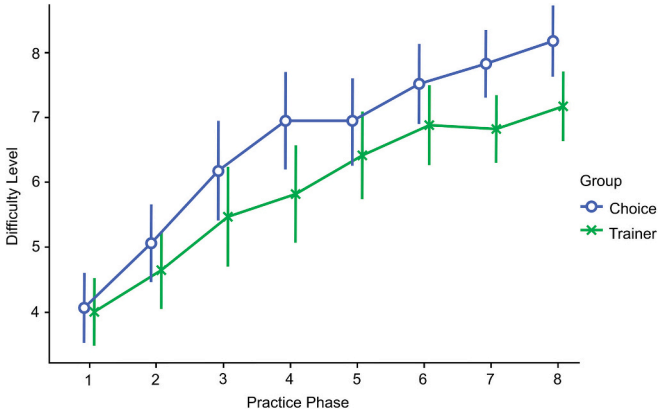


**Fig. 3.** *Difficulty Progression During Practice*. Comparison of difficulty progression over eight practice phase blocks between Choice (identical to Yoked) and Trainer. Difficulty levels between one and ten were chosen independently or, starting at level four for Trainer, adjusted based on error rate in the previous block. A repeated measures ANOVA with the dependent variable 'difficulty level' and between-subjects variable 'group' showed a significant difference between the groups difficulty progression during practice with F (1; 32) = 5.53, $p = .025$, $\eta^2_{\text{part}} = 0.147$.

## 3. Results

### 3.1. Awareness interview, baseline comparison & difficulty progression

As is common in sequence learning studies (Baird & Stewart, 2018; Beißel & Künzell, 2024, 2025; Novén & Karabanov, 2026; Schmidtke & Heuer, 1997; Song, Howard, & Howard, 2007), we conducted a post-experimental interview with every participant to gauge the extent of explicit awareness gained during the experiment to allow for comparison with previous motor sequence studies. Participants were prompted to provide a free description of the task before being asked whether they had noticed and could describe any regularities. Nine out of 51 participants (two each in Choice and Yoke, five in Trainer) could describe a repeating pattern of five or six cube pairs during the first day's testing, which qualified as explicit knowledge of the six-item sequence. It is plausible to infer that motor learning was largely implicit.

Before differences between groups could be assessed to evaluate the effects of autonomy or alternative goal-directed practice on performance and learning, homogeneity of performance between groups at baseline had to be ensured. One-way between-group Fisher's or Kruskal-Wallis ANOVAs for the second tutorial block with the dependent variables 'RT', 'HIT', and 'PR' alongside the grouping variable 'group' revealed no significant differences between groups (see Table 1), allowing for further comparisons.

Likewise, to ensure the validity of our comparisons, we had to assess the difficulty levels of Choice compared to Trainer during practice. Beyond the purely motivational effects of autonomy support on performance and learning, strategies adopted by Choice or consequences of performance in Trainer might impact a comparison if the difficulty levels between groups were to be too similar or if groups were to consistently practice at very high or very low levels (Drews, Pacheco, Bastos, & Tani, 2024; Ziv & Lidor, 2021). A repeated measures ANOVA with the dependent variable 'difficulty level' and between-subjects variable 'group' showed that Choice consistently practiced at higher overall difficulty levels during the practice phase, yielding a significant difference between the groups'

**Table 2**
Post-practice Performance.

| Variable | Choice | | Yoke | | Trainer | | *F* (2;31,3) | *p* |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | | |
| RT [s] | 0.78 | 0.08 | 0.78 | 0.06 | 0.81 | 0.05 | 1.19 | 0.319 |
| | | | | | | | $\chi^2$ (2) | *p* |
| HIT [%] | 76.5 | 10.8 | 80.2 | 9.77 | 82.6 | 6.75 | 2.07 | 0.356 |
| PR [%] | 64.0 | 8.40 | 63.2 | 10.3 | 66.0 | 6.65 | 0.55 | 0.758 |

**Table 3**
Test Phase Motor Sequence Learning: Implicit Learning Scores.

| Variable | Choice | | Yoke | | Trainer | | $\chi^2$ (2) | p |
|---|---|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD | | |
| RT [s] | −0.07 | 0.07 | −0.06 | 0.03 | −0.06 | 0.04 | 0.49 | 0.783 |
| | | | | | | | ***F* (2;48)** | ***p*** |
| HIT [%] | 15.9 | 10.4 | 18.8 | 7.72 | 14.2 | 8.72 | 1.11 | 0.338 |
| PR [%] | 7.72 | 6.36 | 9.71 | 7.97 | 6.99 | 8.82 | 0.56 | 0.577 |

mean difficulty levels, F (1; 32) = 5.53, $p = .025$, $\eta^2_{part} = 0.147$ (see also Fig. 3).

### 3.2. Post-practice performance & learning

As the next step, the groups' general post-practice performance at the beginning of the test phase was compared. The groups' combined means in the first two test phase blocks on day one were compared in one-way between-group Welch's or Kruskal-Wallis ANOVAs with 'RT', 'HIT', and 'PR' as the dependent variables and the grouping variable 'group' (see Table 2). No significant differences were found.

Differences between groups in the degree of successful motor sequence acquisition during the practice phase were assessed next. The ILS was calculated for RT, HIT, and PR from the difference between familiar and random block means of the test phase (see 2.7). The scores were then compared in one-way between-group Kruskal-Wallis or Fisher's ANOVAs with 'RT', 'HIT', and 'PR' as dependent variables and the grouping variable 'group' (see Table 3). No significant differences were found.

### 3.3. Verification of sequence acquisition

The lack of group differences can be explained by either unsuccessful implicit learning and motor sequence acquisition or no influence of autonomy support, contrary to our hypotheses. To exclude the first factor as root cause, we followed up with additional analyses: a within-group comparison of the catch trial blocks three and four, and the familiar blocks two and five in the test phase using either dependent samples *t*-tests or Wilcoxon signed rank tests was calculated for all variables. The Holm-Bonferroni method was used for α value correction. The differences between the learned and random blocks were significant for all groups and all variables (see Table 4).

### 3.4. Retention and transfer of motor sequence

After testing performance and learning, non-temporary learning effects were assessed next with the retention and transfer tasks. The retention test was a repetition of the test phase on day one and a retention ILS (see Table 5) was calculated in the same manner to be compared with the test phase ILS (see Table 3). Repeated measures ANOVAs with the dependent variables 'RT ILS', 'HIT ILS', and 'PR ILS' with the grouping variable 'group' showed no significant main effects of group (see Table 5). For within-group effects indicating the retention of the learned sequence, only the PR ILS was significant (F (1, 48) = 14.1, $p \leq 0.001$, $\eta^2_{part} = 0.227$) with a decrease of ILS means.

Similar results could be found for the transfer task. Performance between the second test phase block on day one and the second transfer task block on day two were compared to assess whether a potentially learned sequence could lead to similar performance or differences between groups. Using repeated measures ANOVAs with the dependent variables 'RT', 'HIT', and 'PR' with the grouping variable 'group', no significant main effects of group were found (see Table 5). For within-group effects indicating transfer effects, significant differences were found for 'HIT' (F (2, 48) = 1.89, $p \leq 0.001$, $\eta^2_{part} = 0.388$) and for 'PR (F (2, 48) = 23.5, p = <.001, $\eta^2_{part} = 0.329$), along with a positive increase of the variables' means (see Table 6).

**Table 4**
*Test* Phase Motor Sequence Learning: Within-group Catch Trial Comparison.

| | Variable | Mean difference | SE difference | W | *p* | $\alpha_{adj}$ |
|---|---|---|---|---|---|---|
| | RT [s] | −0.07 | 0.02 | 3.0 | <0.001 | 0.013 |
| Choice | HIT [%] | 14.4 | 2.53 | 152 | 0.048 | 0.05 |
| | PR [%] | 0.08 | 0.02 | 105 | 0.001 | 0.017 |
| | RT [s] | −0.06 | 0.05 | −7.81 | <0.001 | 0.010 |
| Yoke | HIT [%] | 18.8 | 1.87 | 10.0 | <0.001 | 0.008 |
| | PR [%] | 0.09 | 0.02 | 151 | <0.001 | 0.007 |
| | RT [s] | −0.06 | 0.01 | −5.52 | <0.001 | 0.006 |
| Trainer | HIT [%] | 14.2 | 2.12 | 6.71 | <0.001 | 0.006 |
| | PR [%] | 0.07 | 0.02 | 3.27 | 0.005 | 0.025 |

**Table 5**
Retention Test ILS Means, Repeated Measures ANOVAs, Main Effects of Group.

| Variable | Choice | | Yoke | | Trainer | | *F* (2,48) | *p* |
|---|---|---|---|---|---|---|---|---|
| TP ILS | Mean | SE | Mean | SE | Mean | SE | | |
| RT [s] | −0.07 | 0.07 | −0.06 | 0.03 | −0.06 | 0.04 | | |
| HIT [%] | 15.9 | 10.4 | 18.8 | 7.72 | 14.2 | 8.72 | | |
| PR [%] | 7.72 | 6.36 | 9.71 | 7.97 | 6.99 | 8.82 | | |
| Retention ILS | **Mean** | **SE** | **Mean** | **SE** | **Mean** | **SE** | | |
| RT [s] | −0.06 | 0.01 | −0.06 | 0.01 | −0.07 | 0.01 | 0.035 | 0.966 |
| HIT [%] | 15.3 | 2.10 | 13.7 | 2.10 | 14.3 | 2.10 | 0.313 | 0.733 |
| PR [%] | 4.63 | 1.26 | 5.22 | 1.26 | 2.35 | 1.26 | 1.15 | 0.325 |

*Note*. TP = Test Phase.

## 4. Discussion

This study aims to add to the growing research on sequence learning of complex motor tasks and assesses the influence of the OPTIMAL theories' tenets on performance and learning. We implemented a complex dual task in VR with underlying motor sequences which were ideal for task integration to facilitate acquisition of the sequence. We provided or withheld autonomy support in the form of choice over difficulty adjustment during the practice phase of a bimanual dual task as motivational variable. Based on the OPTIMAL theory, autonomy support should lead to increased motivation and goal-directed behavior (Wong et al., 2015; Wulf & Lewthwaite, 2016), leading participants in the Choice condition to greater overall performance and sequence learning success compared to participants in the Yoke condition (Leiker et al., 2019; Parma et al., 2024; Simmonds et al., 2023). We further postulated that participants in the Trainer condition, provided with goal-directed behavior yet no autonomy support, should perform equally well or better than Choice.

### 4.1. Awareness interview, baseline comparison & difficulty progression

To ensure valid comparisons, participants were carefully assigned to their respective groups based on their performance in the tutorial leading to the main task. The homogeneity of these groups was then tested at baseline and no significant performance differences were found. Changes in performance can therefore be attributed to practice and learning effects. An estimate of the degree of explicit awareness of the underlying motor sequences used in the experiment was also implemented. The interview conducted with the participants showed that the majority of participants were unaware of the sequences, which allows for the assumption that motor learning in this study was largely implicit. While it is not within the scope of this experiment to decisively distinguish between explicit and implicit learning influences, it should still allow for easier comparison with other studies on implicit motor learning. And finally, difficulty progression during practice was significantly different between Trainer and the identical Choice and Yoke. The effect size of $\eta^2_{\text{part}} = 0.147$ represents a large effect yet due to the tasks' inherent variability, we can infer that no drastically divergent practice progressions were followed by the participants. A lack of differences in performance and learning between these groups can therefore be attributed to autonomy effects.

### 4.2. Post-practice performance & learning; retention and transfer of motor sequence

Comparisons for overall performance, for sequence learning and for non-temporary learning effects were implemented to evaluate group differences in this experiment and assess motivational influences. Overall post-practice performance was meant to include all factors that could ultimately influence faster response times, higher hit rates, and precision. This included sequence knowledge, familiarization effects, or attentional and motivational factors. Overall performance was measured at the beginning of the test phase on day one, after a short rest to eliminate symptoms of fatigue. Yet no group differences could be found for any variable, indicating that the participants' general ability to complete the motor tasks was at a similar level. Nevertheless, overall motor performance naturally

**Table 6**
Transfer Assessment, Repeated Measures ANOVAs, Main Effects of Group.

| Variable | Choice | | Yoke | | Trainer | | *F* (2,48) | *p* |
|---|---|---|---|---|---|---|---|---|
| TP Day 1 | Mean | SE | Mean | SE | Mean | SE | | |
| RT [s] | 0.77 | 0.02 | 0.77 | 0.02 | 0.80 | 0.02 | | |
| HIT [%] | 77.7 | 2.34 | 81.9 | 2.34 | 84.3 | 2.34 | | |
| PR [%] | 64.0 | 2.16 | 64.6 | 2.16 | 64.9 | 2.16 | | |
| TrT Day 2 | | | | | | | | |
| RT [s] | 0.80 | 0.02 | 0.78 | 0.02 | 0.80 | 0.02 | 0.450 | 0.640 |
| HIT [%] | 86.4 | 2.07 | 87.4 | 2.07 | 90.4 | 2.07 | 1.89 | 0.161 |
| PR [%] | 70.0 | 1.47 | 70.9 | 1.47 | 72.1 | 1.47 | 0.263 | 0.770 |

*Note*. TP = Test Phase; TrT = Transfer Test.

covers a rather broad range of possible influences on motor behavior. A more focused assessment of the positive effects of motivation on motor learning as postulated by the OPTIMAL theory (Parma et al., 2024; Wulf & Lewthwaite, 2016, 2021; Wulf, Lewthwaite, et al., 2018) was warranted. The degree of success in acquiring motor sequences present in the experiment, represented as an implicit learning score for each variable, was used to assess these effects. However, no significant differences could be found between groups again. While this was unexpected, there are previous studies which did likewise not find practice effects but did find positive effects on retention and transfer tasks (Iwatsuki & Otten, 2021; Lewthwaite et al., 2015; Quan et al., 2024). We had therefore included both a retention and a transfer task in the experiment, yet a similar pattern of homogenous performance and learning in the group comparisons was present.

### 4.3. Verification of sequence acquisition, retention & transfer

Before contrasting these results with our hypotheses, two potential alternative reasons for a lack of group differences had to be tested. One cause might be the absence of implicit learning as the underlying motor sequences used in the experiment were either not perceived or learned. However, the catch trial analysis clearly showed significant differences between familiar and quasi-random motor sequences within each group for all three main variables. As only the sequence of stimuli was changed during the catch trial and all other task conditions were maintained, this difference in performance can be attributed to successful implicit learning and acquisition of the sequence. This is further supported by the within-group results of the retention and transfer tasks: while precision scores slightly decreased, the learning scores for response times and hit rates in the retention test did not differ within the respective groups, indicating successful retention of the learned sequence after one week. There are likewise strong indications for successful transfer of the learned sequence to a similar task using the same sequence. Participants maintained their response times despite having to adapt to new stimulus locations and even improved on hit rate and precision, which showed a significant increase of means. The groups have therefore individually displayed both short-term and long-term success in learning and applying the motor sequences present in familiar blocks. Consequently, the lack of performance and learning differences between groups does necessitate a rejection of our hypotheses.

### 4.4. Contextual implications

We demonstrate that goal-directed practice conditions, whether arising from motivational effects via autonomy support or from coach-driven, performance-oriented guidance, do not significantly influence the performance or learning of complex, sequential motor tasks. Contrary to the OPTIMAL theory's assumptions, we found no advantage for autonomy-supported, self-controlled participants over yoked participants (Wulf & Lewthwaite, 2016). These conclusions match the results of a growing body of research on motivation in motor learning (McKay et al., 2023; Parma et al., 2024). Sanli et al. (2012) already argued several years ago that self-controlled practice effects resulting from motivational variables as argued in the self-determination theory were more assumed than quantified. Recent studies have found similar results: Despite showing increased feelings of autonomy; St. Germain et al. (2021) found no significant learning differences between their Yoke and Choice group which controlled its demonstration schedule. McKay and Ste-Marie (2020) reached the same conclusions in a similar study with choice over ball color as autonomy variable. And as mentioned earlier; Bright et al. (2025); likewise utilizing difficulty manipulation; could show successful learning; retention and transfer; along with high cognitive effort and decreased motivation; yet no significant group differences. However; in a study similar to ours; Quan et al. (2024) tested sequence learning using a simple serial reaction time task and color choice as motivational variable. While they did not find retention effects, a main effect for Choice regarding sequence-specific learning through a task-irrelevant choice could be shown.

Nevertheless, the current body of research on motivational effects on motor processes, as reflected in review studies (McKay et al., 2023; Parma et al., 2024) and studies with large sample sizes (McKay et al., 2023; St. Germain et al., 2023), suggests that self-controlled practice and its effects on motor learning are still lacking evidence or may be absent altogether (Simmonds et al., 2023). These studies simultaneously highlight the need for further studies in this field (Anderson et al., 2021; McKay et al., 2023; Parma et al., 2024). We contribute to this effort by showing that autonomy support with regard to task difficulty appears not to influence performance and learning of complex motor sequences. We further show that goal-directed practice conditions derived from both self-controlled and coach-controlled difficulty adjustments do not significantly affect motor processes compared to a yoked group or to each other.

### 4.5. Limitations

The study would have benefitted from a clearer investigation of perceived autonomy and motivation. Our primary goal was the assessment of measurable performance differences between groups and measurement of motivation could have given insight into underlying mental processes. However, sufficient assessment of motivation is rather challenging, as it has to be differentiated from engagement, fluctuates over time and thus requires rather lengthy surveys to be conducted multiple times over the course of an experiment (Leiker et al., 2016). This would have imposed considerable additional burden on the participants and further extended the study; which led to our focus on performance and learning measures. Autonomy measures might also have ensured a difference in perceived autonomy between groups. As the non-choice groups were not explicitly informed that they were denied autonomy; they might have perceived their practice as self-controlled due to different choice opportunities (St. Germain et al., 2021); such as shifting their focus between the two tasks or exploring alternative movements. The complexity of the task would likely have contributed to this

possibility. Furthermore; Trainer condition participants might have experienced an increase in motivation by the prospect or experience of reaching a higher difficulty level through better performance and resulting enhanced expectancies effects (Ghorbani, 2019; Wulf & Lewthwaite, 2016, 2021). Retrospectively, it has been difficult to distinguish this effect from goal-directed conditions provided exclusively by a coach, underscoring the necessity of including quantitative measures to evaluate motivation in subsequent studies. In the same vein, it remains challenging to distinguish purely motivational effects of autonomy support from individual tactical choice opportunities that can influence motivation and performance (Bright et al., 2025; Drews et al., 2024).

A further potential factor hindering motivational benefits through autonomy support may be external focus of attention, another motivational variable in the OPTIMAL theory (Shooli et al., 2024; Wulf & Lewthwaite, 2021; Wulf, Lewthwaite, et al., 2018). External focus is likely present in this study, as participants would have focused on movement effects, such as hitting the targets, rather than the trajectories of their arms. While external focus has been found to be beneficial to motor performance and learning, it also may share common goal-action coupling mechanisms with autonomy support, potentially suppressing its effects (Shooli et al., 2024; Simpson et al., 2020; Wulf & Lewthwaite, 2016). And lastly, motivational effects on motor learning might just be quite small and not detectable in our current sample size (McKay et al., 2023).

## 5. Conclusion

In the context of implicit sequence learning of a complex motor task, this study demonstrates that goal-directed practice conditions resulting from manipulation of task difficulty do not significantly influence either motor performance or learning. Neither guided practice, as provided by a coach, nor autonomy-supportive practice conditions—hypothesized by the OPTIMAL theory to yield motivational benefits—appear to affect motor sequence learning. Although participants successfully acquired the target sequence, differences between experimental groups were negligibly small or absent. These findings align with several recent studies on motivational effects on motor learning and expand the research to encompass complex motor tasks. More research is still needed to effectively assess the influence of autonomy and motivation on motor learning processes.

## CRediT authorship contribution statement

**Patrick Beißel:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tobias Huber:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis. **Martin Nowak:** Software, Methodology, Investigation, Formal analysis. **Elisabeth André:** Software, Resources. **Stefan Künzell:** Writing – review & editing, Supervision, Resources, Conceptualization.

## Ethical approval

This study was approved by the committee for ethics of the University of Augsburg.

## Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Declaration of competing interest

None.

## Acknowledgements

We thank Nikolai Glaab for his assistance with the development of an earlier iteration of the VR environment.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2026.103483.

## Data availability

The link to all relevant data is listed in the methods section of the manuscript. All data can be accessed freely.

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## Glossary

*OPTIMAL theory:* Optimizing Performance through Intrinsic Motivation and Attention for Learning: motivational and attentional factors contribute to performance and learning by strengthening the coupling of goals to actions (Wulf & Lewthwaite; 2016)
*Enhanced Expectancies:* Learners' self-efficacy expectations towards future tasks, driven by past success or other beneficial task conditions
*External Focus:* Directing attention towards the intended movement effect instead of the movement itself
*Autonomy Support:* Providing learners with a sense of control over their learning process, often by offering choices
*Choice condition:* Condition in which autonomy support is provided while learning
*Yoke condition:* Condition in which learners are matched to another group's choices, and no autonomy support is provided
*Trainer condition:* Condition in which a trainer determines all aspects of practice, and no autonomy support is provided
*SRT task:* Serial Reaction Time task, common method for studying implicit motor sequence learning
*Task integration:* Process of two or more distinct motor tasks being functionally treated as a single task or sequence