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Optimal Training for Movement Acquisition and Transfer: Does 'Externally-Focused' Visual Biofeedback Promote Implicit Motor Learning?

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ABSTRACT

Context: Visual biofeedback has been shown to facilitate injury-resistant movement acquisition in adolescent athletes. Visual biofeedback is typically thought to foster *implicit learning*, by stimulating athletes to focus attention externally (on movement outcome). However, biofeedback may also induce *explicit learning*, if the athlete uses the visual information to consciously guide movement execution (using an internal focus).

Objective: To determine the degree to which athletes report statements indicative of implicit or explicit motor learning after engaging in a visual biofeedback intervention.

Design: Prospective cohort.

Setting: 3D motion analysis laboratory.

Patients or Other Participants: Twenty-five adolescent female soccer athletes (15.9±0.9 yrs, 164.9±5.67 cm, 58.9±10.3 kg).

Interventions: Standard six-week neuromuscular training intervention (three 90-minute sessions/week), with added visual biofeedback sessions (two sessions/week). For the biofeedback training, participants performed squatting and jumping movements while interacting with a visual rectangular stimulus that mapped key parameters associated with injury risk. After the last biofeedback session in each week, participants answered open-ended questions to probe learning strategies.

Main Outcome Measures: Responses to the open-ended questions were categorized as "externally focused" (i.e., on movement outcome, suggestive of implicit learning), "internally focused" (i.e., on movement itself; suggestive of explicit learning), "mixed focus", or "other."

Results: 171 open-ended responses were collected. Most of the responses that could be categorized (39.2%) were externally focused (41.8%) followed by mixed (38.8%), and internally focused (19.4%). The frequency of external focus statements increased from week 1 (18%) to week 6 (50%).

Conclusions: While most statements were externally focused (suggesting implicit learning), the relatively large proportion of internal/mixed focus statements suggests many athletes also engaged in *explicit* motor learning, especially in early practice sessions. Therefore, biofeedback may impact motor learning through a mixture of implicit/explicit learning.

Key words: Anterior Cruciate Ligament; ACL; Biofeedback; Motor Learning; External Focus; Implicit Learning;

KEY POINTS

- **Visual biofeedback may enhance motor learning in people at risk of ACL injury, and is typically thought to promote *implicit* (relatively automatic) rather than explicit (conscious) motor learning**
- **We analyzed verbal reports of adolescent elite female soccer players, in which they described their interactions with real-time biofeedback purposefully designed to promote implicit learning and reduce ACL injury risk**
- **Participants reported adopting a mix of explicit and implicit learning strategies, suggesting that biofeedback not necessarily exclusively promotes implicit learning and that monitoring how people interact with biofeedback is recommended**

INTRODUCTION

There is increasing interest in the application of advanced technologies to promote motor relearning in sports populations. One example of such an application is real-time biofeedback, whereby athletes are presented with visual or auditory feedback for immediate self-modification of a certain aspect of their physiological function (e.g., muscle tension, joint angle[1-4]). In sports research and clinical practice, biofeedback often consists of visually presented information aiming to modify neuromuscular or biomechanical aspects of movement. Specific to anterior cruciate ligament (ACL) injury, different types of visual biofeedback technologies have been used to enhance the acquisition, retention, and transfer of safer movement patterns (e.g. to reduce frontal plane knee abduction angle), often successfully.[2,5-11] Moreover, recent technological developments have allowed for integration of various visual presentation modes (e.g., projector screens, head-mounted displays) with rapid calculation of biomechanical variables (e.g., asymmetrical ground reaction force and/or knee flexion angle), permitting biofeedback stimuli that map to participants' movements in near real-time[12].

Despite subtle differences in methodology, the success of visual-biofeedback manipulations used for ACL injury prevention and rehabilitation purposes have typically been attributed to eliciting *implicit rather than explicit* motor learning processes[7,13,14]. Implicit learning is generally defined as learning that "progresses with no or minimal increases in task-related verbal knowledge (e.g., facts and rules)" (Kleynen et al.,[15] page 9), such that learning occurs 'automatically' with limited conscious awareness[16]. Explicit learning, on the other hand, is a highly cognitive process. Learners typically accrue significant amounts of knowledge that can be verbalized about their performance and deliberately test hypotheses to explore optimal movement solutions. Of these two, various interventions designed to promote implicit learning are *hypothesized* to result in more robust motor learning and transfer[17-20], especially in high injury risk situations, such as a cognitively demanding environment with high performance pressure[21].

Researchers have presumed that employing visual biofeedback will facilitate implicit learning[7,13,14,22] in part because this form of augmented feedback reduces the need for explicit instruction, and diverts attention towards the effects of one's movements (i.e., an external focus of attention) rather than the movements themselves (i.e., an internal focus of attention). However, to our knowledge, there is limited empirical data demonstrating that visual biofeedback does in fact promote implicit learning. In fact, when athletes engage in self-guided 'discovery learning' (and no specific measures are taken to constrain their attention and/or promote exploratory movement), athletes have been found to engage in explicit learning[23,24]. Similarly, when using biofeedback, athletes may consciously investigate how the stimulus responds to their movements (e.g., "if I move my knee to the left I can make the stimulus smaller"), thus promoting explicit learning to achieve desired outcomes.

In short, when using biofeedback to foster motor learning, it is not only relevant what information is delivered (i.e., the accuracy of the information and its relevance to performance), but also how this information is used by the athlete, as could lead to markedly different learning processes and subsequent biofeedback modifications. If athletes use the biofeedback to consciously adjust their movements, and deliberately test hypotheses about how they need to adapt their movement, then they are likely engaging in *explicit learning*. In contrast, *implicit learning* may occur if the biofeedback enables athletes to adjust their movements through unconscious processes, with minimal reliance on explicit, conscious control of movement.

We aimed to investigate whether a published visual biofeedback intervention, which was purposefully designed to induce implicit learning, does indeed promote implicit motor learning processes. For this purpose, we conducted a short explorative secondary data analysis. Specifically, we analyzed written reports that were obtained during a 6-week neuromuscular training intervention that was augmented with real-time biofeedback purposefully designed to promote implicit learning[8]. Using an established method[25] we classified the focus of attention (external or internal) of participants' written self-report after each week of biofeedback training sessions (two sessions/week), to explore the extent to which athletes' statements indicated a more implicit or explicit learning process. An external focus promotes movement automaticity and robustly leads to implicit learning.[26,27] As such, if athletes predominantly reported external focus statements, then we characterized their learning to be more implicit, rather than explicit. By contrast, if athletes predominantly reported internal focus statement, their learning was most likely to have been relatively explicit in nature. We further explored whether participants' self-reported ease of interacting with the visual biofeedback would be associated with the frequency with which they reported statements indicative of explicit learning (i.e., statements containing internal or mixed focus). That is, we hypothesized that athletes would engage in explicit, hypothesis-testing behavior when discovering how the feedback responds to their movements.

METHODS

Population. We conducted a secondary analysis on the data of 25 young (15.0 $\pm$ 1.5 years; 165.7 $\pm$ 5.9 cm; 59.4 + 10.6 kg) healthy female soccer players.[a]

Intervention. All 25 participants completed a 6-week intervention that consisted of 'standard'[28] neuromuscular training (3 x 1.5-hour sessions per week, 18 sessions in total) supplemented with visual biofeedback during certain exercises ('augmented' neuromuscular training; ~2 biofeedback sessions per week; 12 total biofeedback sessions during the duration of the 18-session standard neuromuscular training). The biofeedback training involved participants completing a prescribed exercise while interacting with a visual biofeedback stimulus displayed in near real-time on a projector screen.[b] Biofeedback training was completed using both unilateral exercises (pistol squat, Romanian deadlift; 3x5 repetitions per leg) and bilateral exercises (squat, overhead squat, squat jump, tuck jump; 3x10 repetitions).

As seen in **Figure 1**, the biofeedback was presented as a rectangular shape on a projector screen that responded in near real-time to the biomechanical variables trunk lean, knee-to-hip joint extensor moment force ratio, knee abduction moment of force, and vertical ground reaction force ratio while participants performed various exercises (e.g., double leg squat). While exercising, participants were simply asked to achieve a 'goal shape' (e.g., a perfect rectangle) which would correspond to injury resistant movement (e.g., lesser knee valgus). However, if a participant moved with biomechanics associated with higher ACL injury risk (e.g., greater knee valgus/asymmetrical loading, insufficient knee or hip flexion), then the rectangular stimulus would become distorted in a manner commensurate with the

[a] The prior published work[8] only reports data for 17 participants who completed both biomechanical and brain functional magnetic resonance imaging testing sessions (8 participants did not complete MRI for various reasons [e.g., contraindications to MRI]). This present study, however, reports data for the full dataset who completed the six-week aNMT intervention (*n* = 25).
[b] Stimulus currently patented and adapted for use as part of ongoing clinical trials (NCT # 02933008) (US Patent * US20180125395).

severity of the deficit. Participants were instructed to keep the shape of the rectangular throughout each task but were deliberately not given verbal explicit instructions about how to achieve this. Please refer to previous published work for more detailed description of the intervention[8].[c]

***** Figure 1 near here *****

Written Responses. At the end of the last biofeedback session in each week, participants answered two open-ended questions via written response. These questions were as follows: (1) 'Please share your thoughts about any other aspects of the training, including the stimulus display and the technology used for the training?'; and (2) 'How do you think your movements mapped or corresponded to the movements of the stimulus shape?'. Participants also answered two closed-ended Likert scale questions on perceived responsiveness ('Did the shape feel responsive to your movements?'), and difficulty ('How difficult was it to achieve the goal shape?') of the biofeedback.

To categorize the open-ended questions, we used a simplified version of the standardized scoring system described previously[25]. Specifically, we aimed to establish to what degree a reply could be classified as "externally focused (EF)" (which is indicative of **implicit learning**), "internally focused (IF)" (indicating **explicit learning**), "mixed focused (MF)" (indicating a mixture of the two), or "other". Three raters (EK, TE, JH) established the specific criteria for scoring (see Table 1), and then independently scored all the answers. They subsequently met to discuss discrepancies (initial agreement: 80% of responses), after which they reached consensus on the final scoring. We present the results in two main ways:

[c] Note that we do not present any outcome data related to the biomechanical effects of the intervention. Significant longitudinal improvements in biomechanical parameters (e.g., peak knee abduction moment) have been reported elsewhere[8]. Please also see a series of preliminary studies supporting the enhanced acquisition, retention, and transfer of injury resistant movement when athletes trained with this specific biofeedback system[7,14,29,30].

1) The frequency (%) of external focus, internal focus, and mixed focus responses, combined across two questions and across the six weeks for which responses were collected. This provides insight into how participants generally focused their attention when interacting with the biofeedback practice.
2) The frequency of external focus, internal focus, and mixed focus responses for each week of practice. This provided more information as to how attentional focus changed in the course of practice.

Finally, to explore whether participants were more likely to report statements indicative of *explicit* learning when they experienced *difficulties* using the visual biofeedback, participants completed questions on (1) the degree to which the shape was responsive to their movements, and (2) how difficult they found it to achieve the goal shape. A 7-point Likert scale was used (1: not responsive at all/very difficult; 4: sometimes responses/moderately difficult; 7: responsive all the time/not difficult at all). We calculated the median score and interquartile ranges for these variables. Pearson's r correlations were used to determine if scores on these two questions were associated with the overall frequency with which athletes reported statements indicative of explicit learning (i.e., total number of internal focus/mixed focus statements) rather than implicit learning (total number of external focus statements). For this analysis we created a new variable, using the following equation:

$$\frac{number\ of\ IF + MF\ statements}{number\ of\ IF + MF + EF\ statements}\ x\ 100\%$$

***** Table 1 near here *****

RESULTS

In total, 5 participants did not provide any written responses to the two open-ended questions in any of the sessions. The remaining 20 participants provided 171 written responses in total. Of these, 60.8% concerned ‘other’ statements that did not fall into any isolated or combined attentional focus classification (e.g., ‘it went well’), while the other 39.2% of responses could be assigned a particular attentional focus. Of the latter, most statements were externally focused (41.8%), closely followed by mixed attentional focus (38.8%), whereas 19.4% were internally focused (see Figure 2). Figure 3 depicts the changes in attention focus over time. We observed a relatively gradual increase in external focus statements from week 1 (18%) to week 6 (50% after the final two biofeedback sessions).

All 25 participants completed the closed-ended questions. These questions were both scored on 1-7-point Likert scale warranting median values to be reported. Participants rated the biofeedback as being relatively responsive to their movement (median=6, IQR=1, range=5-7), yet moderately difficult to use (median=4, IQR=1, range=3-7). We found no association between perceived responsiveness and the reporting of internal/mixed focus statements (r=.041, p=.873)[d]. A moderate, non-significant, correlation for perceived difficulty (r=.453, p=.059)[d] suggested that participants who found the feedback easier to use more frequently reported internally/mixed focus statements.

***** Figure 2 near here *****

***** Figure 3 near here *****

DISCUSSION

Our analyses indicate that a visual biofeedback stimulus designed to promote implicit learning for the acquisition, retention, and transfer of improvements in biomechanical factors

[d] Of the 20 participants who provided open-ended responses, 2 provided statements that were exclusively classified as ‘other’. Accordingly, these were not included in this correlational analysis (total N=18).

associated with ACL injury induced both implicit and explicit motor learning strategies in the learners. The majority (42.4%) of the athletes' statements were focused externally, which is associated with more implicit, automatic control of movement[31,32], yet the relatively high proportion of mixed (36.4%) and, to a lesser extent, isolated internal focus (21.2%) statements suggests that many participants also engaged in some degree of explicit learning. This especially seems to have been the case in the early learning phase, given that we observed a relatively low frequency of external focus statements in week 1 (18%) – which then increased gradually over the 6-week practice period (up to 50%).

These unexpected findings highlight that when practitioners develop and use biofeedback specifically to promote implicit motor learning, such a strategy by itself may be insufficient to ensure implicit learning does indeed occur. For the current intervention program, athletes were told to keep the biofeedback stimulus rectangular-shaped, but they were not given any additional instructions or verbal feedback regarding how they should move to achieve this. Even so, when interacting with the biofeedback stimulus, many participants seemed to have gained some explicit, verbalizable knowledge about how they could achieve the desired movement outcome, as evidenced by the written report data. Thus, some participants in the present study seemed to have adopted explicit motor learning strategies during practice (or at least attempted/reported to do so). This so-called 'hypothesis-testing' behavior is a prominent feature of explicit learning[33]. However, we emphasize that such explicit learning should not be considered negative per se, and in fact it may well be very useful to retain new motor skills (e.g., [21,34]). Indeed, prior published work using this specific augmented visual biofeedback system has been effective for the acquisition, retention, and transfer of injury resistant movement[7,8,14,29,30]. That said, it is important to note that (a) the majority of the statements did in fact concern isolated external focus statements (which are associated with implicit learning), and (b) that the motor learning benefits of the biofeedback intervention may to a large extent still be underpinned by implicit processes. Further research could further explore if those individuals for whom the biofeedback elicits a more explicit learning process show different learning outcomes than individuals who largely engage in implicit learning when interacting with the biofeedback.

Our results highlight that practitioners and researchers cannot simply assume that using visual biofeedback during motor learning will result in implicit learning by default. The stimuli used in the present biofeedback intervention simultaneously mapped onto multiple biomechanical risk factors. In theory, this multidimensional approach to fuse and transform data on different aspects of movement potentially limits an athlete's ability to develop an explicit strategy. Even so, athletes still often reported statements indicative of explicit learning. We would hypothesize that related interventions using real-time visual biofeedback isolated to a single biomechanical variable (knee abduction angle only) may induce even greater explicit learning as it would be easier for athletes to discover a strategy for one (rather than multiple) variables[2]. In line with this, our exploratory correlational analysis, though non-significant, might suggest that athletes who found the feedback easier to use more often reported statements indicative of explicit learning (internal and mixed focus statements). It seems that as these athletes identified how the biofeedback responded to their movements, they began to consciously use this knowledge to guide their movements. This in turn may have given them a greater sense of control and perceived ease of use, and possibly more enjoyable/engaging to interact with during training.

This brief report is not without its limitations. First, the open-ended questions that we based our analyses on were not originally devised to infer modes of learning, but rather were intended as evaluation of the intervention and stimulus design more generally. Nonetheless, we ensured reliability of the analysis by going through a rigorous process of scoring, in line with an earlier study[25]. Further, due to missing responses and the relatively small sample, we did not have sufficient data for a more in-depth (statistical) analysis of changes in attentional focus over the entire 6-week training period. We did report some basic changes in frequencies, but more detailed and fine-grained (qualitative) data would be needed to further probe such changes. On this point, using written reports to probe implicit learning has intrinsic limitations (e.g., see [35]). Most importantly, if people move in a fully implicit manner, by definition they would not be able to report on their movements at all (which could partially explain the high percentage of 'other' statements in this study). Therefore, there is a need for a more in-depth study to explore motor learning strategies when engaging with biofeedback. Finally, our study sample consisted of young, female athletes only, which may limit the generalizability of results. For instance, relative to young athletes, older athletes may adopt relatively different learning strategies when interacting with biofeedback. Further, younger athletes may also have found it relatively difficult to answer the open- and closed questions in our study, as these had not specifically been validated for this particular population.

We also emphasize questions had not been validated for use within this specific population, we cannot be sure if the 12–18-year-olds processed the questions as intended, and in some cases may simply not have answered because they did not fully understand the questions. We further recognize that changes in self-reported focus over the six weeks may be, in part, due to the progressive changes in exercises while interacting with the visual biofeedback. For instance, athletes may engage in more (or less) implicit learning strategies when completing relatively slow bilateral squats vs more ballistic tuck jumps. Future research should consider the potential significance of exercise type while using visual biofeedback, including its relative influence on self-reported focus and overall learning strategies.

PRACTICAL APPLICATIONS

Our findings suggest that practitioners and researchers may need to take additional measures if they aim to elicit implicit learning. First, there is always a need for practitioners and/or researchers to monitor what athletes are actually focusing on/attending to when engaging with biofeedback. While we used a relatively elaborate coding scheme in the current paper, a simpler way to achieve this would be to ask athletes to complete a self-report tool that assesses the degree to which they consciously process their movements during practice (e.g., the state-Movement-Specific Reinvestment Scale[36]). Second, if biofeedback were to be used with the specific aim to promote implicit learning, and such checks reveal that athletes are highly conscious of their movements during practice (indicating explicit learning), this may signal to practitioners that additional measures are needed to constrain an athlete's focus or interpretation of the biofeedback. Several methods have been described elsewhere that could be used for such a purpose[27].

In conclusion, our data indicate that real-time biofeedback for ACL injury risk reduction programs may promote both implicit and explicit learning. While many athletes may benefit more from implicit rather than explicit learning strategies, explicit learning may sometimes be more beneficial depending on individual constraints (e.g., working memory capacity or proprioceptive acuity[21]). Future research is warranted to determine whether constraining an athlete's attention to, or interpretation of, their biofeedback could modulate the adoption of implicit or explicit learning strategies. Future research could also establish if 'tailoring' biofeedback (e.g., on a continuum from implicit to explicit learning) helps optimize learning outcomes.

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FIGURE & TABLE LEGENDS

Figure 1: 3D rendering of female athlete interacting with real-time biofeedback stimulus during overhead squat exercise. The shape would deform in near real-time commensurate with biomechanical risk factors associated with ACL injury. Note that the aNMT stimulus presented in some of our prior work (Bonnette, DiCesare, Kiefer, et al., 2019, Bonnette, et al. 2020) was wirelessly transmitted in real time to video eyeglasses worn by participants (similar to figure here), whereas the aNMT stimulus used in the present study was displayed on a projector screen (Diekfuss et al., 2020; Grooms et al., 2018, 2022).

Figure 2. Overall percentage of responses that did contain references to attentional focus classified as either: 'external' (focus on movement outcomes, indicating predominately implicit learning), 'internal' (focus on mechanics of movement, indicating predominately explicit learning) or 'mixed' (both internal and external focus elements within same response). Note that 60.8% of written responses did not fit any attentional focus classification ('other' responses) and were not shown here.

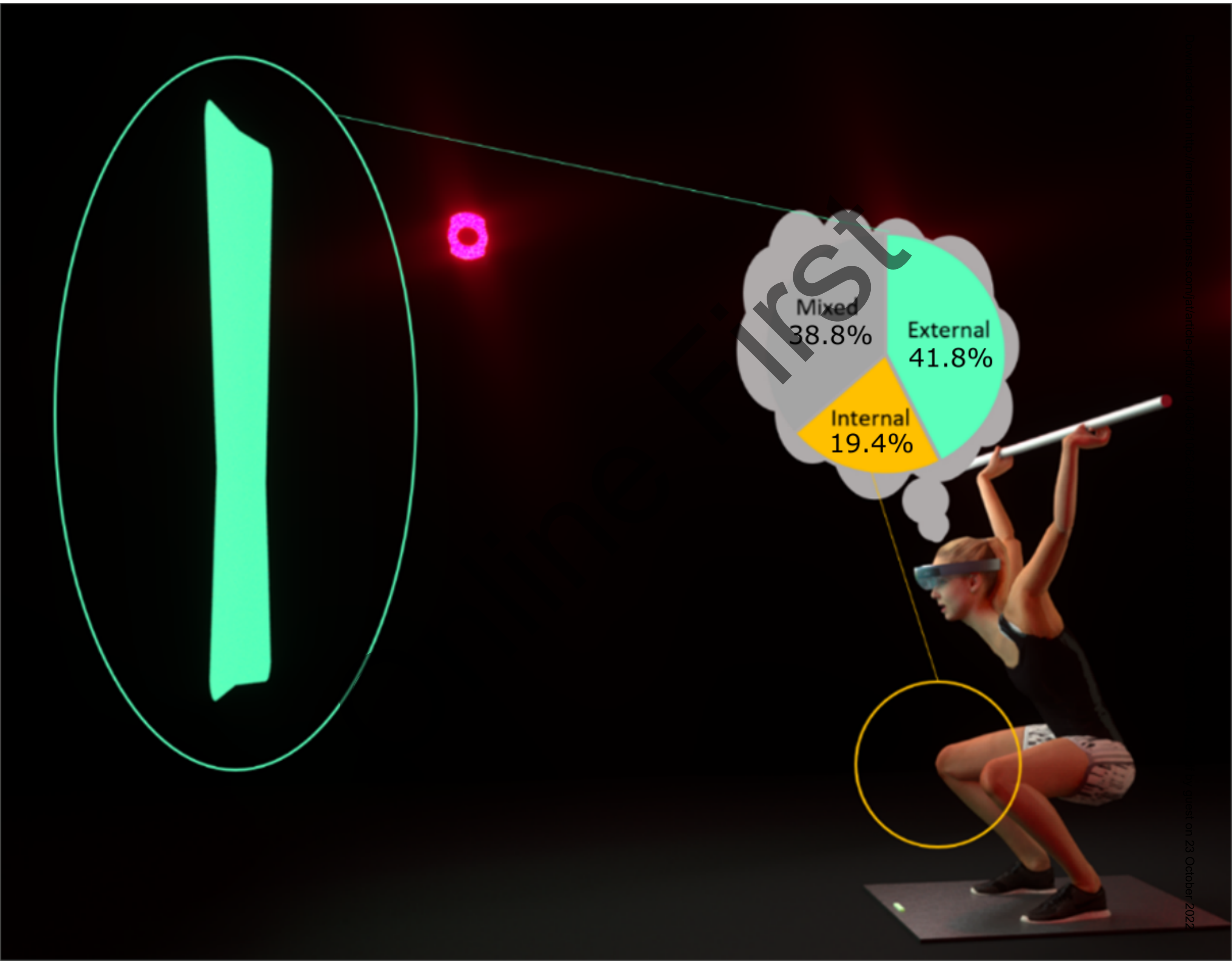
Figure 3. Percentage of external focus, internal focus, and mixed focus statements for each week of training. Note that responses were collected after the second (and last) biofeedback session for each week. For this graph, we estimated the percentages for each category of statements reported for that session (i.e., across participants). NB: not all participants provided responses for each week of practice. Number of participants for whom responses were available are indicated per week.

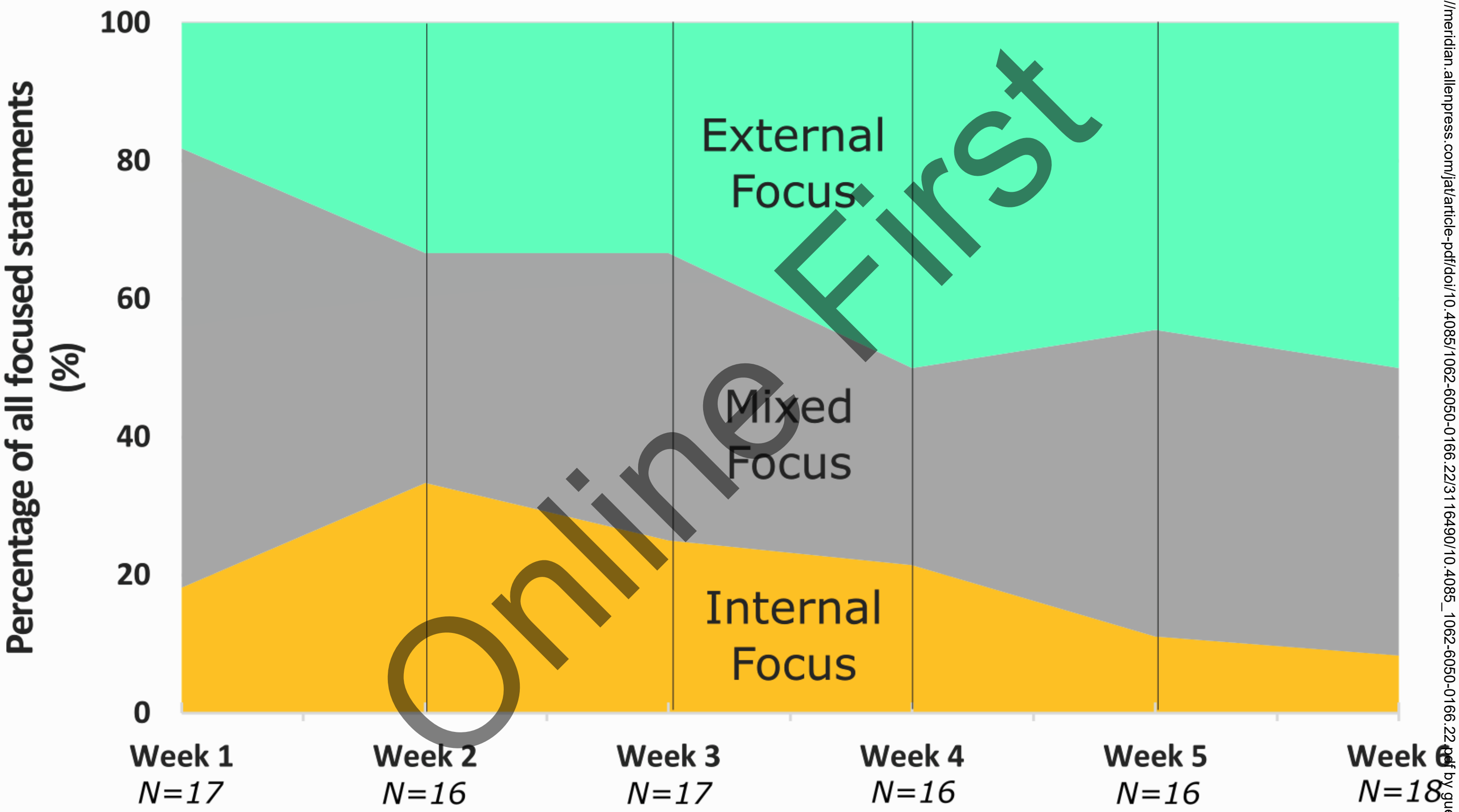
Table 1. Overview of Scoring Methods to Classify the Focus of Attention of Participants' Responses, and the Type of Motor Learning Process These Indicate.

Category assigned to athlete's statement	**Definition**	**Example**	**Code**	**Interpretation in terms of explicit vs. implicit learning**
External Focus	Focus on movement outcome	"… I found it hard to keep [the shape] inside the rectangle"	EF	Indicates more implicit learning[1]
Mixed Focus	Mixture of internal and external focus	"I moved slowly and tried to keep the box straight"	MF	Mixture of both implicit & explicit learning
Internal Focus	Focus on movement mechanics	"… my hips weren't in line with the rest of my body, or my knees went over my toes."	IF	Indicates more explicit learning
Other type of statement	No clear focus evident	"I think everything was good and everything worked well"	OTHER	No clear indication of either motor learning strategy

NB: Examples are from the current data set.

[1]Please note that, by definition, it is very difficult to probe implicit learning, as it's typically defined as the *absence* of explicit knowledge. That said, written reports can be used to explore whether individuals predominantly use internal or external focus of attention during learning. These concepts largely (though not perfectly) map onto implicit vs. explicit motor learning. That is, external focus is known to promote automaticity of learning, and is a recognised implicit learning intervention (e.g., Van Abswoude et al., 2021; Kal et al., 2019; these articles also summarise other commonly used implicit learning interventions). In contrast, internal focus is known to promote conscious control of movement, and thereby contributes to explicit learning. Hence, athletes who more often report external rather than internal focus statements, are more likely to have engaged in *implicit* learning during the preceding practice session. A similar scoring method has been used to explore the attentional focus of therapists' instructions and feedback in our previous work (Kal et al., 2018).


Mixed
38.8%
External
41.8%
Internal
19.4%



100
80
60
40
20
0
Percentage of all focused statements (%)
External Focus
Mixed Focus
Internal Focus
Week 1 N=17
Week 2 N=16
Week 3 N=17
Week 4 N=16
Week 5 N=16
Week 6 N=18