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Quantification of Information Transmission in Signal Play-calling for NCAA Division 1 College Football: A Comprehensive Literature Review

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ABSTRACT

Background: To gain a competitive advantage in National Collegiate Athletic Association (NCAA) Division 1 American college football, teams often use a coded, hand/body gesture-based play-calling system to communicate calls to student-athletes on the field. **Objective:** The purpose of this study is to apply cognitive engineering concepts toward the improvement of signal transmission such that a realistic amount of data signaled will be received and understood by the student-athlete. **Methods:** Partnering with an NCAA coaching staff, information transmitted via signal-based communication pathways were quantified to inform the design of their signal system. Quality control coaches, practitioners of football signalling characterization and design, used an autoethnographic frame to train researchers on the communication protocol standards. A comprehensive literature review of sources from 1900 to 2019 was conducted to examine information transmission, signal-gesture taxonomies, sign-language recognition, and code design. Findings were applied to the signal system to quantify the information contained in the transmission between the signalling coaches and the student-athletes. **Results:** Results found that the observed signal system transmits an average of 12.62 bits of information on offense and 12.92 bits on defense with 23% and 12% redundancy, respectively. **Conclusion:** Recommendations were provided to the coaching staff regarding code optimization and gesture design to improve student-athlete performance.

Key words: Information Theory, Communication, Cognition, Engineering, Gestures, Sports, Comprehension

INTRODUCTION

Hartley introduced information measurement in 1928 as it relates to electrical communication (i.e., physical rather than psychological considerations) and points out the fundamental idea that the (abstract) capacity to transmit information implies a (concrete) quantitative measure of information (Hartley, 1928). Shannon and Weaver expanded on these ideas in The Mathematical Theory of Communication and define information as, "the reduction of uncertainty," which summarizes an abstract concept through mathematical deduction (Shannon, 1948). This difference in uncertainty from the state prior to an event and the state after an event is the quantity of information transmitted. The amount of uncertainty reduced by the event is defined to be the average minimum number of true-false (or yes-no) questions that would have to be asked to reduce the uncertainty (Ramsden, 2009; Wickens, Hollands, Banbury, & Parasuraman, 2013). The answer to a yes-no question conveys exactly one unit of information, since answering either true or false conveys the same meaning about its truth. This minimal element of information is called a "bit," short for "binary digit" (Shannon, 1948). To quantify the number of bits transmitted by a stimulus, event, or message, there are three statistical and qualitative variables that must be known about the information source: the number of total possible events, the probability of each event, and the context or sequence in which each event occurs. These shall each be examined in this assessment. In general, any information pathway can be illustrated with the analogy of an electrical communication, as shown in Figure 1.

Recently, many American college football teams have adopted a faster (i.e., up-tempo) offensive strategy that eliminates the huddle for shorter time between plays, more total playing time (Brown et al., 2020), and better chances of

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forcing mistakes by the defence (Reid et al., 2020). To eliminate the huddle, student-athletes now receive play-calling signals from coaches on the side-line, rather than from the quarterback in a huddle, and go right to the line once the ball is spotted (Hicks et al., 2019). Teams have various ways of signalling, including picture boards (Figure 2), word/color/number boards, and hand/body/verbal signals (Figure 3) which are coded to prevent the opponent from learning the plays (Brown et al., 2020; Hicks et al., 2019; Reid et al., 2020). Each signal transmitted by a signalling coach represents information the student-athlete needs, such as a play, a formation, or a cadence. There are often redundant signallers to help the student-athletes and dummy signallers to confuse the opponent. A National Collegiate Athlete Association (NCAA) Division 1 university that partnered with this research team used hand/body gestures between the 2018 and 2019 football seasons, of which there were over 300 unique signals, as well as picture boards to communicate calls. Due to all the information to remember and recognize, the amount of information transmitted immediately before a play may affect the student-athlete's total cognitive burden.

Information Theory is about understanding the transmission of information and, in the context of college football, is useful for minimizing the cognitive burden on student-athletes. On the field between plays, student-athletes are bombarded with information from numerous sources including signallers, teammates, opponents, fans, and officials (Hicks et al., 2019). They must receive, process, and react to the most critical information within a few seconds for optimal competitive performance and minimal time between plays (Reid et al., 2020). The information pathway between signallers and student-athletes is of critical concern because it facilitates strategic play-calling information and is one of the few information sources that is deliberate and adjustable. By optimizing this information pathway to reduce student-athlete cognitive burden, coaches can increase student-athlete performance while minimizing time needed between plays. To quantify and assess this information pathway, information should be measured in bits.

Information issues are categorized as either overload or underload. Overload is when "information received becomes a hindrance rather than a help, even though the information is potentially useful" (Bawden & Robinson, 2009). Underload is not having enough information. In the play-calling signal pathway, overload could occur for many reasons, including too many calls in the playbook, too much

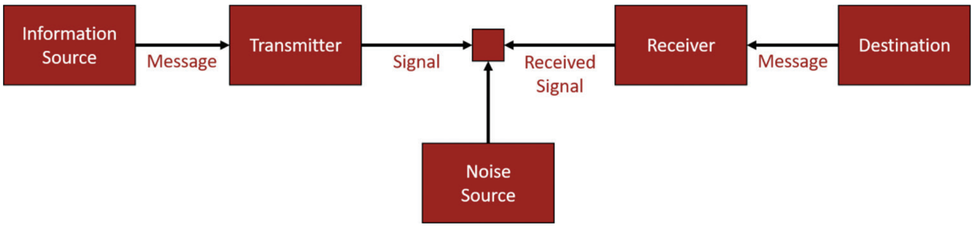

Figure 1. The information pathway (*communication system*) as defined by Shannon and Weaver (Shannon, 1948)

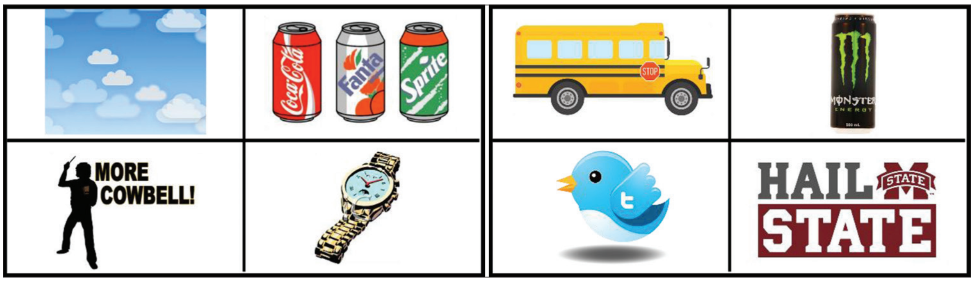

Figure 2. Four-quadrant picture boards with logos/images (Brown et al., 2020; Hicks et al., 2019; Reid et al., 2020). (Clip art courtesy of: http://clipart-library.com.)

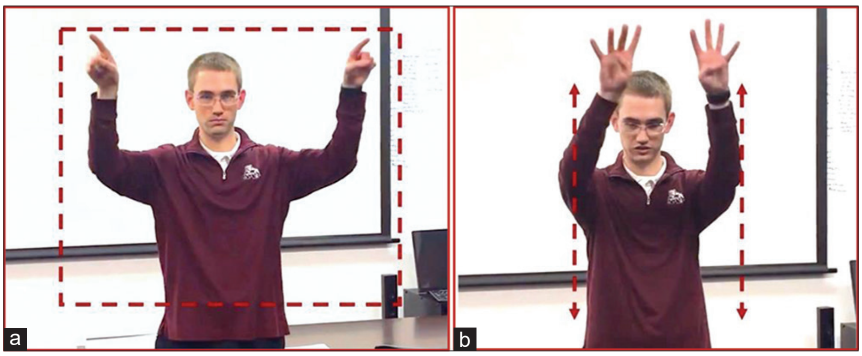

Figure 3. (a) drawing a rectangle in the air for "Box", (b) waving hands up and down with fingers outstretched for "Smoke"

complexity or length of each signal, or too many signallers. Underload could occur if the opposite were the case, leaving student-athletes unprepared or left to make their own judgements.

The goal of this analysis is to determine the amount of information transmitted via play-calling signals to an American football player between offensive and defensive plays of a Southeastern Conference (SEC) football game, and to identify opportunities to optimize the information transmission for maximizing student-athlete recognition, performance, and minimizing time between plays. By drawing parallels to broader domains, such as information transmission and quantification, memory storage, gestural taxonomy, semiotics, and linguistics, proven methodologies can be applied to the context of football play-calling signals and perform a valid assessment of the signal system. The result is a formal evaluation that verifies its strengths and suggests improvements.

METHODS

Study Design

This study uses a comprehensive literature review to find validated methodologies for analyzing gestural signals and quantifying information transmitted along a defined pathway, as well as interpreting the results of information quantification and their effect on performance. The review is supported by inputs and feedback from subject matter experts (SMEs)—professional coaching staff familiar with all communication methods used within the NCAA Division 1 American football. The researchers were trained by the SMEs regarding the quantities and forms of various football signals, and literature was reviewed to learn of proven information theory methodologies. These methods were then applied to quantify the information transmitted using this signal system.

Procedure

Knowledge elicitation and training with subject matter experts

The NCAA Division 1 football program that participated in this exploratory study employs multiple quality control coaches for both the offensive and defensive sides of the sport; these coaches served as SMEs for this study. The role of a quality control coach at the NCAA Division 1 level of American football is focused on preparing both the offense and defence by analyzing opponents' strategies through film and statistical analysis to augment and supplement the team's own schemes based on patterns identified in the actions of the upcoming adversary. The SMEs who participated in researcher training have worked for numerous NCAA football teams and have a thorough understanding of football play-calling signalling systems through their experience as assistant coaches. The SMEs also have the knowledge to provide estimates of the type, frequency, and accuracy of the team's signals. The signals and play calls demonstrated by the SMEs were not current signals, as those are closely guarded for security purposes; rather the signals were a standard baseline commonly found in collegiate football programs that utilize the up-tempo, no huddle system of play-calling. Through a combination of in-person responses and textual explanations, the SMEs provided expert descriptions of game scenarios, quantities of calls and call types, estimates of call frequency, play-calling issues and successes, and data about contextual and unique circumstances.

Data extraction

After training was completed, the first data items to process were the videos where SMEs demonstrated signalling examples (not currently in use). Each signal's name, description, and motion breakdown were documented. Motion breakdown refers to analyzing the different movements and holds comprising the signal (Liddell & Johnson, 2013; Vogler & Metaxas, 2004). After the signal data was organized, the SMEs were asked to provide several potential play-calling elements (number of cadences, formations, plays, etc.). This data allowed for bit calculations to be performed. After receiving the number of elements, a qualitative scoring system was used to assign probabilities.

Search strategy

As in the other three papers associated with this football communication series (Brown et al., 2020; Hicks et al., 2019; Reid et al., 2020), the EBSCO for Academic Libraries search engine was used. EBSCO, a library tool offered at research institutions, enables the researcher to search for keywords across all academic literature-based databases at once. EBSCO includes 539 databases that range from PubMed, to IEEE, to Google Scholar and all the well and lesser-known scholarly search databases. Searching within EBSCO ensures inclusion of most scholarly research and exclusion of predatory journals. Based on an extensive literature review conducted in 2019 using this tool, there were no studies found that assess the impact of play-calling signal transmission in American football. In fact, there is no evidence of studies of information transmission in any sport and little research into the types of coded non-verbal communication that exists in many athletic activities. This is substantiated by a search of all available journal articles published from 1900 to 2019 using keywords such as, "signal" OR "sign" OR "gesture," and a broad search in EBSCO for keywords such as, "information transmission sport" OR "gesture information sport" OR "signal information sport" OR "baseball sign," etc. Therefore, a quantitative meta-analysis is not feasible given the current state of the literature, so an applied literature review was performed instead by extracting relevant theories from existing studies and using those theories to deconstruct an NCAA Division 1 football play-calling signal system.

Inclusion Criteria

To be included as a valid source, studies had to meet the following criteria: (a) the study was peer-reviewed, published by a reputable publication, or cited by at least ten sources; (b) the study introduced or assessed concepts covering the technical, semantic, or effectiveness aspects of information theory; (c) the article was written in English; and (d) the full text of the study was accessible. All researchers independently reviewed articles and screened for inclusion criteria. Each article was documented by the researcher in a centralized spreadsheet, where duplicates could be excluded.

Results

Figure 4 illustrates the literature search and review process.

Application of Ideas

There are three levels to any communication problem regarding how a message is transmitted, as defined by Shannon: precision (the semantic problem), accuracy (the technical problem), and effectiveness (the effectiveness problem) (Shannon, 1948). The semantic problem is addressed first, by observing the content and meaning of play-calling signals. By extracting the message from the signal (i.e., decoding), the signal event can be defined (e.g., as one message). Next, with a signal event defined and data characterizing the entire signal system (e.g., the playbook and associated signals), the information transmitted can be quantified and the technical problem addressed. Lastly, the effectiveness of the signal system can be assessed by applying proven theories that improve the quality of gestural signals and coded messages.

Rather than treating each signal as a sum of multiple stimuli (e.g., two hands making a series of gestures), each signal represents a single unique stimulus. This unique stimulus is the smallest unit of useful information in the signal system and can be treated as a single event. This event is not quantified by a single bit, but rather one information-filled message that can be learned and recalled from a single storage register in the memory (G. Miller, 1956). Each storage register can contain a different amount of information in bits, but only store one message. For example, the ideas, "my age," (one number) and "my house," (a large entity composed of many characteristics) are single messages stored in memory, but each contains drastically different quantities of information. The point is that these ideas are stored efficiently as one

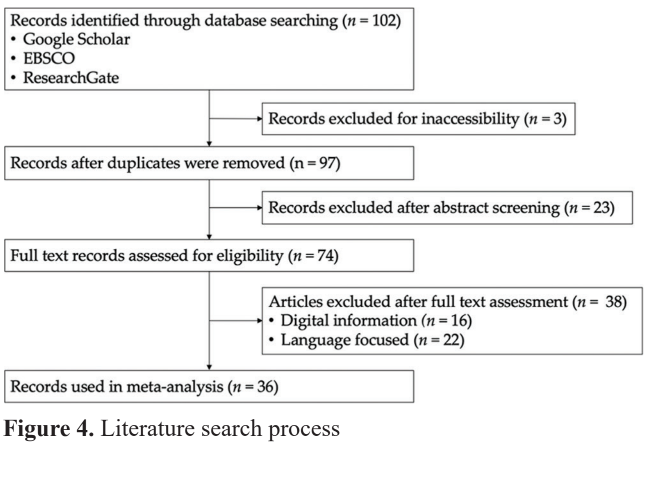

Figure 4. Literature search process

message, just as different play-calling signals are one message, but each can contain varying information.

Since the focus of this study is on the transmission, rather than the storage of information, the research team is primarily concerned with the capacity of the student-athlete as a channel, not a storage device. The channel capacity, or bandwidth, of a human is the "greatest amount of information they can give us about the stimulus on the basis of an absolute judgment" (G. A. Miller, 1956). Since each signal is a discrete stimulus among a large number of possible stimuli, recognizing signals is an absolute judgement task (Wickens et al., 2013). This discrete nature allows the maximum possible stimuli transmitted per amount of time to be measured for the average human, which has been shown to be around 25 bits/second under optimal conditions, but more realistically 10-12 bits/second under fair conditions (G. Miller, 1956). This is a critical upper bound to consider when designing an information transmission system for human receivers under non-ideal conditions, such as the play-calling signal system during an NCAA Division 1 football game.

Signals & calls

Signalling in American football refers to the coded messages coaches send to student-athletes on the field to communicate instructions for the upcoming play. The participating NCAA Division 1 football program uses hand and body signals as well as picture boards to convey information during game play. Prior to playing, coaches create the playbook and student-athletes create signals associated with the calls to increase signal-meaning association. Signals are called by multiple signallers (e.g., coaches or athletes on the sidelines), each dedicated to a type of call. Some signallers are live (i.e., relay the real signals), some of whom are dead (i.e., relay fake signals), and some hold up picture boards (Brown et al., 2020). The dummy signals are used to confuse the opposing team, who may be attempting to learn the plays by associating signals with observed calls. To signal a call, a signaller gets the attention of as many student-athletes as possible, makes the hand/body gesture two-to-three times, and confirms receipt when all student-athletes look away. If the signal is not received, noted by a confused look or gesture from a student-athlete, the signaller repeats the signal until receipt is confirmed.

To solve the semantic problem of play-calling signals, the content of the signals and the meanings behind them must first be understood, since the medium and format affects the quantity of information needed to convey an idea. For instance, if the message, "tree," were to be communicated, (a) the word tree could be spoken verbally, (b) a picture of a tree could be shown, (c) the word could be transmitted via text, or (d) another coded message format or sign could be used. Despite being a single message with the same meaning in each case, the context and medium used affects the total information transmitted (Wickens et al., 2013). The initial assumption was that signals were complex spatial actions, composed of multiple arbitrary gestures that only provided meaning as a sum of their parts. These arbitrary gestures must be learned (just as words associated with an idea in a new language are learned). This led the research team to create a taxonomy of football signals based on other forms of gestural communication and non-verbal languages, such as American Sign Language (ASL) (B. Koons, J. Sparrell, & Thórisson, 1991; Liddell & Johnson, 2013). But by breaking down the signals into smaller gestural units—dubbed "cheremes" by Stokoe (Stokoe Jr, 2005)—the research team discovered that those units became meaningless (in the context of football) and therefore did not contain information. Each signal is actually a single gesture, typified by the movement and/or hold of the fingers, hands, arms, and body, that represents one concept or message (Kendon, 1986; McNeill & Liddell, 2000). Since these gestures are standardized—predetermined as part of a system and standalone—not accompanying verbal communication, they are considered "autonomous gestures," are organized into a gesture system, and are the predecessor of sign language (Kendon, 1986). In this context, a gesture is a single message, defined as, "a sign or string of signs transmitted from a sign producer, or source, to a sign receiver, or destination," where the signaller is the source and the destination is the student-athlete (Sebeok, 2001). To further refine this idea, a sign is defined as "any physical form that has been imagined or made externally (through some physical medium) to stand for an object, feeling, event, etc.," (Sebeok, 2001). In general, a sign is composed of two parts: the *signifier* or form (i.e., how it is presented) and the *signified* or concept (i.e., what it represents) (De Saussure, 2011). However, Aristotle theorized that the third dimension of a sign is what it *means* (psychologically and socially), and that these three dimensions are simultaneous (Sebeok, 2001). That is, under a given context, the form, the concept, and its meaning are connected, so when a human receives a sign, they simultaneously perceive its meaning. This idea is important to prove that a signal received by a football player transmits one coded message, which can be stored in a single memory register, but may vary in bits of information depending on the message.

Play-calling signal examples provided by the SMEs (shown in Figure 3) illustrate how signs (e.g., finger, hand, arm, and body gestures) are used to mean concepts (e.g., names of calls), which in the context of the play-calling signal system provide meaning and critical information (e.g., where to line up, what snap to move on, where to move after the snap) to the student-athletes on the field.

A photo or logo on a picture board (Figure 2) is also a form of a sign and within this context can be treated the same as finger/hand/arm/body signals regarding information transmission. Just like a gesture, an image or symbol can represent many concepts based on the context: obvious and widely accepted meanings (e.g., a picture of Snoopy could mean, "Snoopy," "dog," or "cartoon,") and context-specific meanings (e.g., your dog is named Snoopy, therefore, a picture of the cartoon reminds you of your dog). So, when an image is part of a defined signal system, like the play-calling signal system, the image only represents one concept, which is associated with a single meaning. For example, a photo of the Hollywood sign on a picture board within the play-calling signal system could signify a play called "Los Angeles," which means, "go left."

Number of events

The total number of events defines the amount of uncertainty, with more events creating higher uncertainty (Wickens et al., 2013). To quantify the amount of information in a single event, the total number of events must first be determined. Using data from the SMEs, the research team determined that there are commonly 2 poster boards with 4 quadrants each; 30 cadence calls, 10 formation calls, and 300 play calls on offense; and 10 front calls, 55 blitz calls, and 50 coverage calls on defence. The calculation of the total possible events is the product of possible calls for a given play. Therefore, there are 8 possible poster board events, 90,000 possible events for an offensive play, and 27,500 possible events for a defensive play.

The amount of information in one event, H_S, given N possible events, is $\log_2 N$, assuming all events have equal likelihood of occurring (Wickens et al., 2013). This value provides an upper bound for the amount of information transmitted and is an easy to calculate benchmark if event probabilities are unknown.

Probability

Assuming each event will have equal probability is not realistic, however; a subset of common cadences, formations, and plays will be called more frequently than certain specialized or complex calls. So, different probabilities must be incorporated to have an accurate understanding of the information load. The empirical probability of a single call is not easily determined, but the assumption can be made that the distribution of call frequency will resemble a normal distribution, based on the Central Limit Theorem. To estimate the probability of calls, fit to a normal distribution, SMEs were asked to qualitatively score the call frequency in terms of very common, common, infrequent, and rare, with these frequencies corresponding to one standard deviation, two standard deviations, three standard deviations, and four standard deviations, respectively. Therefore, a very common call is 68% likely, a common call is 27% likely, an infrequent call is 4.7% likely, and a rare call is 0.3% likely.

The probability, P, of an individual event, such as a specific very common cadence call, is the conditional probability that a cadence call (1 in 10 potential cadence calls) is very common (68% chance). The information for this event is calculated by $\log_2 \frac{1}{P}$ (Wickens et al., 2013). For a category of events (e.g., any very common cadence call, of which there are 3), the amount of information of any event in the category is given by $\sum P_i \left(\log_2 (\frac{1}{P_i}) \right)$ (Wickens et al., 2013). Summing the categories gives a total information quantity for that call (e.g., cadence calls), which can be added to the total for each play (e.g., a cadence, formation, and play for offense; front, blitz, and coverage for defence). This provides an average information load, or bit count, for any signal on offense or defence.

The purpose of assigning probabilities is to account for the varying amount of information within each signal, which is based on the frequency it is used. In other words, a very common event transmits less information than a rare event (Wickens et al., 2013). The example that Wickens et al. (Wickens et al., 2013) use to illustrate the concept is the probability of rain in the desert. A sunny forecast conveys little to no information since it is expected, but a rain forecast transmits much more information due to its rarity (Wickens et al., 2013).

Context

The call probabilities used here are based on long-term averages and the Central Limit Theorem, which provides a steady-state estimate for information transmission. However, certain circumstances within the football game will radically alter the number of possible play calls, which creates transient probabilities. These transient probabilities stem from the context of the football game, and, since the context will alter the number of outcomes, the context cues add information independent of the playbook. For example, the down, score, time left in the game, and the defensive formation all influence what calls are made. Furthermore, play calls can change meaning based on the context of the football game, which requires student-athletes to be vigilant of their surroundings.

Outlier cases such as two-point conversions, fake punts, and Hail Mary passes will have lower event uncertainty due to the limited number of these plays in the playbook. Based on feedback and experience from the SMEs working at multiple football institutions, they estimated that a team generally has approximately five possible two-point conversion calls, five Hail Mary calls, and three fake punt calls for each game.

Redundancy

A bit count that considers context and event probability will be less than a bit count for equally likely events. This reduction of net information from context and event probability (while still conveying meaning) is known as redundancy and is calculated as a percentage of the maximum information, such as, $1 - \frac{H_{ave}}{H_{max}}$. The benefit of redundancy is illustrated with the following sentence: "Wh-t th-s sug-est- is t-at ma-y of t-e le-ter- ar- not ne-ess-ry fo- com-reh-nsi-n" (Wickens et al., 2013). In this example, the full meaning of the sentence can still be understood despite the missing letters (i.e., a loss of information). In terms of signal security (i.e., sending the signal without a loss of information), more redundancy makes a signal more secure because more information can be lost without losing meaning). Note that the portion of the message that can be omitted is a result of statistical likelihood, not desired outcome on the recipient's behalf (Shannon, 1948).

Noise

In football signalling, there are many sources of audible and visual noise, such as crowd noise, athlete and coach conversations, waving/cheering fans, lights, screens, coaches running around off the field, and student-athletes running around on the field. While this noise is distracting and can dramatically affect attention, memory, performance, and the detection of some signals (Hicks et al., 2019), most sources do not affect call sign transmission, as they exist in a different channel. Travers (Travers, 1964) found that when multiple information channels are filled (audio, visual, haptic), users tend to block out all but the one of greatest value. The channel that concerns viewing and understanding the hand and body signals is purely visual and can only be disrupted by noise that obscures the line of sight between the student-athlete and the signaller.

The information lost to noise is the difference between the information sent by signallers—transmission information (H_T)—and the information received—response information (H_R). This is challenging to measure empirically, however, based on the SMEs' experience working with elite athletes at the highest levels of collegiate and professional sports, signals are rarely received incorrectly ($H_R \neq H_T$) or not received at all ($H_T = 0$). This is likely the result of a well-designed system, flexible redundancy in the signalling (i.e., signal repetition until receipt confirmation), and the diversity of signals. Additionally, measuring and quantifying H_R would be difficult, time-consuming, and out of the scope of this research.

Dummy signallers

Dummy signals produced by "dead" signallers do not reduce uncertainty for student-athletes and therefore do not add information to their information pathway. However, at the beginning of the drive (or whenever signallers are changed), student-athletes require some information to distinguish which signallers are live and which are dead. This amount of information is likely 1 to 2 bits, depending on the number of dead signallers, and should only be transmitted once the first time the student-athletes receive signals. After the first time, student-athletes know which signallers to look to for live calls, and no longer receive this information.

If the dead signallers do not continue to affect the student-athletes' information transmission, why are they important? There is a second information pathway to consider, which is between the signallers and the opposing team members who are trying to steal signals. Since the opposing team is attempting to learn signals by matching signal information to observed actions, more signal information for the same number of observed actions makes matching more difficult. Therefore, to decrease the probability of signals being stolen, their signal information should be maximized. Since the opposing team does not know the signal system, each signal provides information based on the total number of events (seen in one game), the frequency of those events (how many times have they seen the same call), and the context (when they've seen the signal). Therefore, by increasing the number of signals, via dummy signals, and decreasing frequency (signalling random meaningless signals with little repetition), the information transmitted to the opposing team is increased.

Information Quantification

In this section, the information transmitted between all play-calling signallers and student-athletes during an average football game (as identified by the SMEs) is calculated.

Conditions

To produce reasonable calculations based on a realistic scenario, assumptions must be stated and the conditions of the information transmission scenario outlined. Circumstances outside these conditions could affect the quantity of information transmitted, so to reduce dependent variables for a more accurate result, conditions in Table 1 were chosen as the control.

Table 1. Assumed conditions for calculating information transmission in a realistic, game-time football scenario

1	Football team has the ball (offense signals only)
2	Mid-field position (no major obstructions or sharp angles)
3	Mid-quarter with full play clock (no time constraints)
4	Loud stadium (average level of audible noise)
5	Starting line student-athletes (high skill/experience level)
6	Full coaching staff (all seven signallers present)
7	Home game (familiar with environment)
8	Opponent is equal seed (neither formidable nor easy)
9	Favourable weather conditions (optimal temperature, no rain)

RESULTS

Calculation of Bit Count

The first calculated quantity was the upper bound for information transmission. This quantity used the data provided by the SMEs and the formulas listed in. The result is 16.46 bits of information for offense and 14.75 bits of information for defence. When factoring in different probabilities, the results shift to 12.62 bits of information on offense and 12.92 bits of information on defence. This makes offensive calls 23% redundant and defensive calls 12% redundant. The purpose and frequency of picture board use is too varied to have a known probability distribution, so information is calculated using only number of events. With four quadrants per picture board and a maximum of two boards, the net maximum information they transmit only 2 bits. Outlier cases such as fake punts, two-point conversions, and Hail Mary passes contain 1.58 bits, 2.32 bits, and 2.32 bits of information, respectively. Table 2 provides the results of these calculations.

Table 2. Summary of results of average bits per play call component and the redundancy of each

	Average Bits	Redundancy
Offense	12.62	23%
Formation	3.73	24%
Cadence	1.88	43%
Play	7.00	15%
Defence	12.92	12%
Front	2.48	25%
Blitz	5.31	8%
Coverage	5.13	9%
Picture board	2.00	0%
Fake punt	1.58	0%
Two-point conversion	2.32	0%
Hail Mary	2.32	0%

DISCUSSION

Interpretation of Bit Count

The bit count measures the amount of information transmitted through the information pathway during a single instance of communication between a signaller and student-athlete. Several studies have measured the effect of information quantity on various types of performance (e.g., error rate, recall), which together can be used to interpret the bit count calculated here. Miller (G. A. Miller, 1956) found that the correct selection of stimuli begins to degrade after the sample grows larger than seven bits, which demonstrates the existence of information overload. Schnore and Partington (Schnore & Partington, 1967) correlated recall errors with the number of bits in several images, and found the error rate increased as bit count increased. Anderson and Fitts (Anderson & Fitts, 1958) measured information recall as the bit count per message increased due to the inclusion of numerals and colors. They found that performance increased to an optimal point, then began to degrade with further information (Anderson & Fitts, 1958). Mackenzie (Mackenzie, 1995) investigated human computer interface performance and used bit count to quantify the difficulty of a task. Harder tasks, which were described by higher bit counts, incurred longer movement times (Mackenzie, 1995).

The research indicates that the relationship between information quantity and performance follows the phenomenon known as the inverted "U" curve, where the optimal amount of information lies between the state of overload and underload (Hwang & Lin, 1999). Sicilia and Ruiz (Sicilia & Ruiz, 2010) applied this concept to online retail and confirmed the existence of the "U" curve by measuring subject performance with exposure to varied levels of information. It is clear that too little to or too much information can lead to poor performance. The optimal information amount will therefore inform the trade-off between simplicity and complexity in the playbook.

By combining the bit count with current student-athlete performance, a benchmark can be established to quantify a good range of information. The value of this measure would become apparent in the event of major changes to the playbook. For example, if problems were to emerge from major changes to the playbook, the current bit count can be compared to the past bit count to determine if information is the root of the problem.

Interpretation of Redundancy Percentage

The calculations show that redundancy is present in football signals. Redundancy is the potential loss in information, which can be interpreted as the difference between the maximum possible information and the actual information necessary to be transmitted. This could mean that incomplete signals are transmitted, but the practical reality is that the entire signal is needed to understand the intended meaning (De Saussure, 2011; Sebeok, 2001). SMEs at the participating institution have confirmed this in the context of football. Given that the signal is indivisible from a perception standpoint, the redundancy seen here is due only to a loss in information from context and a wide range of event probability.

Since the higher the frequency of the call, the less the information it contains (compared to the maximum), a larger proportion of high frequency calls to low frequency calls will increase the redundancy in the signal system. This means that the redundancy percent functions as a diagnostic of the proportion of frequently used calls to infrequently used calls.

This redundancy percent is useful because understanding call frequency can bolster performance (Abernethy, Gill, Parks, & Packer, 2001). If student-athletes see a frequently used set of signals over the course of a season, then perception of those signals will occur more quickly. This allows for shorter time between plays, but it carries risk of the opposing team decrypting the meaning of the signals. The more frequently a signal is used, the more chances the opposing team has to learn its meaning.

Much like the inverted "U" curve, the ideal amount of redundancy in the context of football will be between opposing extremes. While a crisp percentage for optimality cannot be assigned at this point, the concept of diminishing marginal returns can be applied (Niño-Mora, 2006). In terms of football, there reaches a point where increases in the benefits of redundancy will be outweighed by an overreliance on a frequent set of calls. Not all opponents will be equally proficient at decoding the meaning of the signals, so the optimal percentage will be based on the opposing team's ability to decode the signal. If the opponent is highly proficient at decoding signals, than higher redundancy (i.e., high proportions of frequently called plays) will become a liability.

Findings Summary

After a quantitative and qualitative assessment of the information transmission pathway in an NCAA Division 1 American football's signalling system, the research team concludes that the signalling system appears to be well-designed but has opportunities for further optimization. First, the signals are already highly minimized. Throughout the entire signal system, all sample signals are short and minimally complex. Signal simplicity is preferable in the context of football because student-athletes must memorize dozens of unique signals. Lengthy signals add cognitive burden with no gain in signal security. Aside from being simple, the signal gestures have deeper meanings to the student-athletes because they were included in the creation of all the signals. This draws on shared cultural experiences and aids in signal learning.

Another reason the signals are optimized is due to their gesture design. There are four categories that describe gestures: iconic, emblematic, pantomimic, and deictic (Capone & McGregor, 2004; Rimé & Shiaratura, 1991; Singleton & Shulman, 2013). Iconic gestures closely resemble what they are describing (Özyürek, 2014), emblematic gestures function as a metaphor for a certain meaning, pantomimic gestures manipulate an invisible object, and deictic gestures involve pointing at an object. Most of the gestures for the participating football institution are iconic in nature, which means their intended meaning is close to their form.

In terms of student-athlete performance, the SMEs shared that mistakes due to misunderstandings of signals are not commonly made during a football game. This allows the research team to reason that the current information load and redundancy percentages are manageable, otherwise errors would be more prevalent. Finally, noise in the visual channel is not a systemic issue because student-athletes, as mentioned above, are already able to maintain a high-level of performance and comprehension. Minimal perception issues indicate that visual noise is already accounted for by the coaching staff.

While gathering data and talking with SMEs, the research team took note of best practices used in their football signalling. The first is that signallers on the side-line send their respective signals in unison. Having each signaller send their signal at the same time reduces the amount of disorder on the side-line and thus reduces cognitive burden. The second finding was that student-athletes signal amongst themselves while on the field. This finding came as a surprise, but this technique is powerful from a performance perspective because inter-player signalling acts as an extra measure of redundancy. Some positions, such as the cornerback, might be exposed to more visual noise due to their field position, and the inter-player signalling ensures the correct message reaches these student-athletes.

Limitations

Given the constraints that (a) the number of total calls and signal events cannot be changed (i.e., the play book is created by the coaching staff and its size is based only on how many calls it takes to win), and (b) the student-athletes create the signals and assign meaning to them (i.e., externally generated signals would be less meaningful and less memorable), there are only a few variables that can be controlled through recommendations.

Recommendations

Code design

The play-calling signal system is a coded message system, and therefore can be optimized using the same tools. A key consideration in code design is balancing and maximizing *economy* and *security* (Wickens et al., 2013). Economy refers to the amount of conveyed information per length/complexity of a signal (i.e., efficiency). Security refers to the signal's quality (i.e., resistance to information loss). However, these concepts can oppose each other; therefore, the two must be balanced for optimal signal design. To maximize efficiency, the Shannon-Farro principle can be applied. This principle states that any code or message using short signs, characters, or symbols to communicate a longer meaning is most efficient when the message's length is proportional to the quantity of conveyed information (Shannon, 1948). This relationship, known as Zipf's Law, occurs organically in natural language—frequent (i.e., high-probability) words are typically short (e.g., a, the, is) conveying less information (Ellis & Hitchcock, 1986). In other applications, this idea is similar to *compression*: the removal of all unnecessary parts of the message (i.e., redundancy) plus the removal of the least informative parts (i.e., some information loss, with little decrease in understanding) (Travers, 1964). In practice, this would mean guiding the student-athletes as they generate new signals, to assign the shortest, fastest, or simplest signals to the most frequently used calls. For the rare calls, signals should be longer, slower, or more complex. Signal Detection Theory identifies that a frequent signal leads to a lower beta (i.e., the threshold between a detected and undetected signal) and can therefore be detected with less sensitivity. Applying this to football signals, higher probability calls can contain less information creating the advantage that less sensitivity is required to detect them. With this understanding, increasing the efficiency of the signals (i.e., decreasing the length or complexity) should not make the signals harder to detect. In terms of memory, studies confirm that the length of message, not the amount of information contained within, is what makes it harder to remember (G. Miller, 1956), so by increasing the message efficiency, it should also be easier to remember.

Adding security to a coded message system means increasing quality as a function of a message's *importance*. Commonly, the most frequent messages are the most important; if they are also the most efficient, as previously discussed, there is an increased risk of information loss due to the consequences of that loss. To prevent loss, signal quality should be improved. One effective strategy is to add redundancy. Wickens, Prinet, et al. conducted a meta-analysis on various auditory and visual cues inside an aircraft cockpit and found that redundancy in the cues increased security (i.e., accuracy) (Wickens, Prinet, Hutchins, Sarter, & Sebok, 2011). Redundancy could be added in the traditional sense of the word, with repetition, or by including any non-essential part of the signal. In practice, this would mean guiding the student-athletes as they generate new signals to add information to higher risk calls to ensure they are received correctly. For example, if a call involves a series of coordinated routes with a high-risk of failure if someone misses their route, the signal for this play could use two hands making the same motion to make it more obvious and harder to mistake.

Redundancy has been shown to increase total information transmission in some cases, but only if there is an issue with the stimulus. That is, if the signal is process-limited (signals are too similar and difficult to distinguish) or state-limited (difficulty seeing the signal due to low salience, high noise, etc.), total information in the pathway could increase (Garner, 1974). However, this should not be an issue in this context, since the signal sample in this study showed high diversity (no two signals were similar) and high visibility (few issues receiving signals from the field).

Gesture design

The representative signal sample demonstrates that iconic signals are already predominantly used to send call information from the side-lines to the student-athletes. However, since team members create their own signals, the research encourages student-athletes to develop iconic gestures over the other gesture types (emblematic, pantomimic, and deictic). Iconic gestures have been linked to greater retention and lower response time in experiments due to their similarity to the concept being described. Özyürek (Özyürek, 2014) measured response time to vegetable chopping gestures, and strong iconic associations to the task had lower response times. Levantinou (Levantinou & Navarretta, 2015) found that iconic gestures supported memory encoding and recall. So et al. (So, Sim Chen-Hui, & Low Wei-Shan, 2012) found that iconic gestures aided memory recall when used alongside language. Kelly et al. (Kelly, McDevitt, & Esch, 2009) found that iconic gestures aided in language learning and Caselli (Caselli, n.d.) found that iconic gestures, along with frequency and context, aided in sign language and spoken language learning. Hostetter (Hostetter, 2011) also notes that iconic gestures are more communicative than other types of gestures. Campisi and Özyürek (Campisi & Özyürek, 2013) studied language acquisition and found iconic gestures to be a scaffolding technique for learning. It is important to note that gestures can belong to more than one category of gesture type (iconic, emblematic, deictic, pantomimic), and when a gesture does not neatly fit into one category, its iconicity can be viewed as "a matter of degree rather than kind" (Krauss, Chen, & Gottesman, 2000).

The side-line signals essentially form another language for the football players to learn, since each signal has a mapping to its core meaning (Kendon, 1986). However, unlike language, the signals change over the course of a season, causing student-athletes to have to learn numerous signals and their meanings. For this reason, the development of iconic gestures to create deeper meaning and thus reduce the cognitive burden on the student-athletes is recommended.

Future work

One potential area for further research and application is to investigate different football play calling systems. For example, systems such as the Coryell, Erhardt-Perkins, and West Coast style are in use throughout professional football (Crepeau, 1993; Fast & Jensen, 2006; Thornton, 2018). Studying these systems could spark new ideas for coding the playbook and managing the information load. Another area for future application is in dealing with future informational issues experienced by the football team. Now that football signalling has been studied from an Information Theory perspective, the informational component within a football game can be studied more precisely. For example, if a side-line signal is not performing well, then one solution is to evaluate its iconicity. Finally, the probabilities and event numbers are not exact due to security concerns, but refining the calculations with more contextual circumstances, exact event count, and more precise probabilities will produce better calculations.

Applications for Coaching Practitioners

Just as American football game demands have caused student-athletes to evolve physically over time (Shelly et al., 2020), so too have the cognitive demands. During one author's experience playing football at the collegiate level during the late 1990's and early 2000's, the huddle was the primary source of communication. A student-athletes would receive the offensive play call on the sideline from the head or assistant coach verbally. That athlete would then run into the huddle and share the abbreviated play name with the quarterback (abbreviated so that there was less to remember and repeat to the other student-athletes as there was limited time between plays). The quarterback would then use their wrist-worn playbook guide to reference the associated play and then call out to the student-athletes in the huddle the full list of requirements at which point the quarterback would "break" the huddle and all would align properly in their positions. Pre-existing knowledge of the play by all student-athletes was required but questions and clarifications could occur in the huddle on a limited basis. Since that time, the no-huddle system, largely known to have originated out of Oklahoma State University and Oregon University in the later 2000s (Hruby, 2011), has evolved to many forms and across many organizations at the collegiate and high school levels. While the National Football League (NFL) largely still adheres the traditional huddle method, professional football players will likely have experienced at least one no-huddle offense on their journey to signing with an NFL team. These cognitive demands on student-athletes have changed as have the expectations coaches have for their players. Because of these increased demands, some coaches are more likely to involve the student-athletes in the design of the play calls, as discussed throughout this narrative. As the total number of plays grow and the complexity of the sideline signals increase, the mental aspect of the game has evolved along with the physical. Just like strength coaches must be aware of the physical training limits of their athletes, coordinators must be aware of the student-athletes' cognitive limits including how many information bits a person can consume in a short amount of time within a noisy environment under a high amount of duress. The authors who are coaches on this paper have experienced coordinators creating increasing complexity within their signal calls to provide more information while attempting to prevent the other team from interpreting or "stealing" the call over the course of the game. At some point, however, the information is too much even for experienced student-athletes simply because the athletes, and humans in general, have limitations. Wickens et al. (2013) identifies that an average person in an average situation can receive and retain between five and nine bits of new pieces of information for a limited amount of time. All students-athletes on the field should be familiar with the play calls meaning that more bits could be transmitted as they aren't seeing signals for the first time. Student-athletes with years of game experience should retain even more bits due to a greater level of general game awareness (Shelly et al., 2019). Even freshman or people playing in a game for the first time should slowly be able to recognize and retain information over the course of a season. But the critical takeaway that we as coaching practitioners using our autoethnographic frame would stress is that the maximum number of bits that student-athletes can retain in signals will vary from athlete to athlete. Creating cognitive baseline for athletes is just as critical as when strength coaches baseline their physical capabilities (Burch et al., 2019). Cognitive testing equipment is available from companies like Senaptec™ in the form of shutter glasses and sensor stations used to train response and reaction times as well as to capture that baseline. While these tools help to improve mental game speed and awareness, they can also be used in signal call training as well. A combination of making play calls as intuitive as possible while giving the athletes mechanisms to train cognitively will be necessary as the game of football gets faster and the play call strategies increase in complexity.

CONCLUSION

Many NCAA Division 1 American college football programs have moved away from huddle formation to share information about the play call. Instead, at the start of each new play, the student-athletes align in or near their expected position and look for the play call instruction to come from the coaching staff on the sideline of the football field. These teams are often using a coded, posterboard and hand/body gesture-based play-calling system to communicate calls to student-athletes on the field. To investigate the average number of information bits comprised in these signals and communicated during these play call transmissions, this research team partnered with an NCAA coaching staff to understand the standard no-huddle, play calling procedure of the sport. Quality control coaches, practitioners of football signalling characterization and design, worked with this team using an autoethnographic frame to explain the protocol and train researchers on the standards often used at the collegiate level of competition. A comprehensive literature review was performed using keywords defined by SMEs within a commonly used library database search tool, EBSCO. One-hundred and two literature references were discovered through this search method but only 36 were utilized due to the predefined inclusion and exclusion criteria. Because no literature could be found defining information transmissions in American football, let alone any elite-level sport, a review was conducted to examine information transmission, signal-gesture taxonomies, sign-language recognition, and code design in all areas such that the findings could be re-examined for purposes of the game of football. Findings explaining information transmission were applied to the signal system to quantify the number of bits contained in the communications between the signalling coaches and the student-athletes. Results from the review as applied to the play calling system assessed found that the observed signal system transmits an average of 12.62 bits of information on offense per play and 12.92 bits on defence per play with 23% and 12% redundancy, respectively. Despite the complexity of the play calling and overall number of plays being a high count—as identified via the experience encapsulated by the authors who comprise former student-athletes and coaches at the collegiate and professional levels of the sport—the existing system was optimized. Two primary recommendations based on literature were provided to the coaching staff regarding (a) code optimization and (b) gesture design to improve student-athlete performance. For code optimization, there is a balance of economy and security where economy refers to the amount of information in the signal and security refers to its quality. These are competing characteristics where one attribute is often increased at the expense of the other. Therefore, coaches must consider attributes such as compression (removing all unnecessary components that add little to no information) and importance (higher emphasis on critical signals or parts of signals through redundancy practices). Also, iconic gesture can be used in gesture design to improve learning and recall. A risk noted in this study, however, is that the constant changing of signals from week-to-week or game-to-game to minimize opponent signal theft causes student-athletes to learn numerous signals and their meanings and, sometimes, different meanings for the same signals during the same season. Due to the low number of errors in student-athletes properly decoding the signals, the coaches have not experienced this as a problem.

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