Performance and Motor Control Characteristics of Functional Skills

CHAPTER 7

Concept: Specific characteristics of the performance of various types of motor skills provide the basis for much of our understanding of motor control.

After completing this chapter, you will be able to

- Describe Fitts' law and explain how it relates to the speed-accuracy trade-off phenomenon
- Define the term *prehension;* describe a prehension example; discuss, from a motor control perspective, the relationship among the components of a prehension action; and discuss the role of vision in prehension
- Describe how handwriting provides a good example of the concept of motor equivalence and the influence of vision on handwriting
- Describe the difference between symmetric and asymmetric bimanual coordination, and discuss why asymmetric bimanual coordination is more difficult to learn than symmetric
- Describe the rhythmic relationships associated with walking and running gait patterns, the role of maintaining head stability during locomotion, and the characteristics associated with gait transitions that occur at certain speeds of locomotion
- Describe the three movement phases of catching a moving object and the role vision plays in each phase, and answer the question of whether it is important to be able to see one's hands throughout the flight of an object to catch it
- Discuss how vision influences the striking of a moving object and what that influence tells us about the control of this type of action
- Describe how vision influences locomotion when the action goal is to contact an object or avoid contact with an object in the environment

APPLICATION

Appropriate instruction and practice intervention procedures are important to develop to help people acquire or rehabilitate skills effectively and efficiently. As you saw in chapters 5 and 6, a basic understanding of motor control theory and the sensory processes involved in motor control form important parts of a foundation on which to base the development of these procedures. Consider the following two examples. If a person were having difficulty reaching, grasping, and drinking from a cup, how would the therapist develop an appropriate intervention strategy to help the person perform this type of skill? An important part of the answer to this question comes from research concerned with the motor control of prehension. Or, suppose a beginning student in a tennis class is having problems learning to serve because he or she cannot coordinate the ball toss and racquet movement that must simultaneously occur to perform a successful serve. Motor control researchers have identified some distinct characteristics of bimanual coordination that provide teachers and coaches some insight into how to overcome the tennis serve problem.

These two examples illustrate situations in which an understanding of motor control processes and characteristics associated with specific motor skills can give you insights into helping people overcome performance problems in skill learning and rehabilitation contexts. We could consider many more examples, but these two should allow you to see how to apply an understanding of performance and motor control characteristics to working with people in their pursuit of learning or rehabilitating motor skills. In the chapter discussion, you will be introduced to specific performance and motor control characteristics associated with a variety of skills. Some of these are unique to a specific motor skill; others are common across several skills. If the skills you expect to help people in your future profession learn or rehabilitate are included, you can discover the specific performance and motor control characteristics you will need to take into account to facilitate the acquisition of these skills. If the skills you expect to help people learn or rehabilitate are not included, the information presented should provide you with a knowledge base from which you can make specific applications to those skills.

Application Problem to Solve Choose a motor skill that in your future profession you expect to help people learn or rehabilitate. What are the performance characteristics of this skill that will pose distinct difficulties for these people as they learn or rehabilitate the skill? What motor control characteristics should you take into account in the strategies and procedures you use to help these people learn or rehabilitate the skill?

DISCUSSION

The motor control theories discussed in chapter 5 and the roles of sensory information discussed in chapter 6 were derived from researchers' observations of people performing a variety of everyday and sport skills in many different situations. These observations have established that each type of skill involves distinct performance characteristics that are essential to consider in our understanding of motor control processes and to provide guidance for practitioners as they help people learn or rehabilitate skills. In the following sections of this chapter, we will consider several of the more prominent types of motor skills researchers have investigated with these goals in mind. These skills are considered in no particular order but are presented to provide a variety of skills to establish how the concepts discussed in chapters 5 and 6 can be applied to specific functional motor skills.

It is important to point out that in the discussion of these skills, we will limit the discussion of the sensory systems' involvement in motor control primarily to the role of vision. Although, as you read in chapter 6, vestibular, tactile and proprioceptive sensory information play roles in the motor control of functional skills, discussion of those roles is beyond the scope of this introductory book.

SPEED-ACCURACY SKILLS

Many motor skills require a person to perform with both speed and accuracy. For example, kicking a penalty kick in soccer, pitching a fastball for a strike in baseball and softball, playing a song on a piano at a fast tempo, and speed typing all require fast and accurate movement to achieve successful performance. For these skills, the speed and accuracy demands are determined by the skill itself. Other motor skills require limb-movement accuracy but not speed. For example, many **manual aiming skills**, which involve hand movement to a target, require that the hand arrive at the target but at a speed that the performer determines. Such skills include putting a key into a keyhole, placing a pen in a penholder, typing on a computer keyboard, and threading a needle.

For both types of speed-accuracy skills, those that require fast and accurate movement and those that require accurate movement at an unspecified speed, we commonly observe a phenomenon known as the **speed-accuracy trade-off**. This means that the accuracy requirements of the movement will influence the movement speed so that an emphasis on accuracy will reduce speed, while an emphasis on speed will reduce accuracy. Thus, we typically "trade off" speed for accuracy, and vice versa. Consider how this trade-off would occur in the examples of the two types of skills described above. For a penalty kick in soccer, when a player tries to kick the ball at the fastest speed possible, the typical result is an inaccurate kick. Conversely, when the player emphasizes accuracy by trying to kick the ball to a small part of the goal, the result is often a ball kicked too slowly to get past the goalkeeper. For the example of putting a key in a keyhole, moving the key too quickly toward the keyhole typically results in missing the keyhole, whereas an emphasis on accuracy results in slower hand movement.

Fitts' Law

Research evidence demonstrating a speed-accuracy trade-off can be traced back to an 1899 publication by R. S. Woodworth, who was one of the pioneers in the study of motor control (see Elliott, Helsen, & Chua, 2001, for a review of Woodworth's experiments and influence on research). For the following half century, evidence for a speed-accuracy trade-off in motor skill performance had become so common that a mathematical law was developed to predict movement speed given specific accuracy characteristics. This law, which has become known as Fitts' law, was described by and based on the work of Paul Fitts (1954). It has become one of the most significant "laws" associated with human performance. In science, a *law* refers to a situation in which a result, or outcome, can be predicted when certain variables are involved.

Fitts' law predicts the movement time for a situation requiring both speed and accuracy in which a person must move to a target as quickly and accurately as possible. The variables that predict the performance outcome are the *distance* to move and the *target size.* According to Fitts' law, if we know the spatial dimensions of these two variables, we can predict the movement time required to hit the target. In mathematical terms, Fitts' law describes this relationship as

$$\mathrm{MT} = a + b \log_2(2D/W)$$

where

MT is movement time
a and b are constants
D is the distance moved
W is the target width, or size

That is, movement time will be equal to the $\log_2$ of two times the distance to move divided by the width of the target. As the distance to move increases, the movement will take longer and as the target size becomes smaller, movement speed will decrease to ensure the movement is accurate. In other words, there is a speed-accuracy trade-off.

Fitts indicated that because of the lawful relationship between target size and movement distance, the equation $\log_2(2D/W)$ provides an **index of difficulty (ID)** for speed-accuracy skills. The

manual aiming skills motor skills that involve arm, hand, and/or finger movement to a target; e.g., putting a key into a keyhole, threading a needle with thread, and typing on a computer keyboard.

speed-accuracy trade-off a characteristic of motor skill performance in which the speed at which a skill is performed is influenced by movement accuracy demands; the trade-off is that increasing speed yields decreasing accuracy, and vice versa.

Fitts' law a human performance law specifying the movement time for an aiming movement when the distance to move and the target size are known; it is quantified as $\mathrm{MT} = a + b \log_2(2D/W)$, where a and b are constants and W = target width, and D = distance from the starting point to the target.

index of difficulty (ID) according to Fitts' law, a quantitative measure of the difficulty of performing a skill involving both speed and accuracy requirements; it is calculated as the $\log_2(2D/W)$, where W = target width, and D = distance from the starting point to the target.

LAB LINKS

Lab 7a in the Online Learning Center Lab Manual for chapter 7 provides an opportunity for you to perform reciprocal tapping tasks with characteristics that will allow you to experience how Fitts' law describes the speed-accuracy trade-off.

index specifies that the higher the ID is, the more difficult the task will be. This is because more difficult tasks will require more movement time.

Figure 7.1a shows several examples of reciprocal tapping task dimensions that would characterize different IDs. Figure 7.1b shows approximate movement times for tasks with these, and other, IDs to illustrate the relationship between task difficulty (ID) and movement speed when people are instructed to move accurately—that is, hit the target.

Fitts' law applies to many skills. Fitts based his original calculation on a reciprocal tapping task in which participants made repetitive back-and-forth movements as fast as possible between two targets for a specified period of time. For this task, they were told to place an emphasis on accuracy.

Although Fitts' law was developed on the basis of performance on a laboratory task, it is important to note that the lawful speed-accuracy relationship also applies to a wide range of motor skill performance situations. For example, research shows that when people perform manual aiming tasks, such as throwing darts at a target, reaching or grasping containers of different sizes, playing a piano, moving pegs from one location to insert them into a hole, and moving a cursor on a screen to a target, their actions demonstrate movement time characteristics predicted by Fitts' law.

An example of the application of Fitts' law to human computer interaction tasks was demonstrated by a conclusion provided in a study by El Lahib, Tekli, and Issa (2018). Based on their work with the pointing task, a common computer task in which a person points at an object on the monitor with a pointing device or by touching the object with a finger, they argue that Fitts' law "remains one of the central studies that have mathematically modeled the pointing method. . ." and has been found to "be a good predictor of the average time needed to perform a pointing task" (p. 16).

If we apply Fitts' law to the sport skills described earlier in this section, it should be possible to see the implications of this law for instruction and practice. For example, suppose a soccer player is asked to practice scoring a goal on a penalty kick by kicking the ball so that it travels as fast as possible to each of three different-sized areas in the goal. Fitts' law predicts that the highest speed will occur for the ball kicked to the largest area. Conversely, the slowest speed will characterize the ball kicked to the smallest area. Later in this book (Unit VI), we will discuss the practice conditions that will help a person achieve both speed and accuracy in these types of situations.

Open- and closed-loop motor control processes related to the speed-accuracy trade-off. Researchers have proposed several hypotheses to explain the motor control processes related to the speed-accuracy trade-off. Most have elaborated on Woodworth's (1899) original hypothesis, which was that two motor control processes operate during the rapid limb movement to a target. One, which occurs initially and moves the limb into the vicinity of the target, is an *open-loop control* process where the initial movement's speed, direction, and accuracy are under CNS control without feedback. The second process involves *closed-loop control* in which visual feedback about the limb's relative position to that target is used to guide the "homing in" phase of the limb to ensure its accurate landing on the target. The hypotheses proposed since Woodworth's have focused on providing more detailed descriptions of the motor control activities involved in either the open- or closed-loop, or both, phases of the movement. However, all agree that, as we discussed in chapter 6, the amount of time available is the primary determinant of whether a person can make movement corrections as the limb

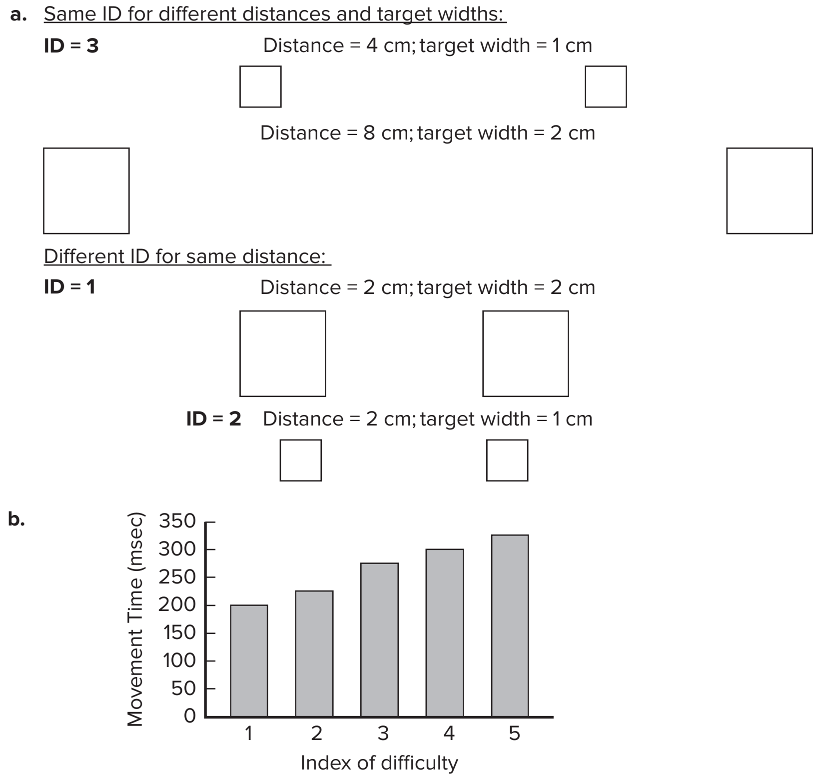

FIGURE 7.1 (a) Examples of indexes of difficulty (IDs) for reciprocal tapping tasks with different target size and/or distance characteristics. Task difficulty is indexed according to the ID such that the higher the ID is, the more difficult the task is. The ID is calculated according to the Fitts' law equation: ID = $\log_2$ (2 • Distance/Width). (Note that *D* is measured from the near edge of each target.) (b) Approximate movement times (in msec) for each tap of reciprocal tapping tasks of five different indexes of difficulty.

nears the target. This means that if the movement speed is too fast during the initial open-loop phase, there will not be sufficient time for visual feedback to generate a movement adjustment as the limb nears the target.

The role of visual information in the speed-accuracy trade-off. When we consider the involvement of our sensory-perceptual systems in the performance of a speed-accuracy skill, such as putting a key into a keyhole, vision plays a predominant role in enabling successful performance. However, it is worth noting that blind individuals have also shown the influence of Fitts' law, as demonstrated in the study by El Lahib and colleagues (2018) in which a vibrating touch screen was used for blind participants to tap specific shapes on the screen.

The specific role played by vision in speed-accuracy skills depends on the phase of the limb movement. Although the hypotheses described in the preceding section proposed two distinct movement phases for these skills, an open-loop and a closed-loop phase, researchers generally agree that including a third phase is important to understand the role of vision in the control process. This additional phase involves the preparation of the movements required to perform the skill.

A CLOSER LOOK

The Controversy Related to Explaining Fitts' Law

Researchers have not agreed on a motor control explanation for the speed-accuracy trade-off. Below is a sampling of some of the prominent hypotheses that continue to have proponents. It is important to understand that these hypotheses relate to explanations for the speed-accuracy trade-off associated with rapid manual-aiming tasks, which were the types of tasks involved in the initial demonstrations of the trade-off. (See Elliott et al., 2001, for a more detailed discussion of these, and other, hypotheses and of the research evidence related to them.)

- **Intermittent feedback hypothesis.** Crossman and Goodeve (1983) proposed that open-loop control is involved in the initiation of a rapid manual aiming task. But as the arm moves toward the target, the person intermittently uses feedback to generate submovements, which are small corrections in the trajectory, until the target is contacted. Movement time (MT) increases for longer distances or narrower targets because the number of corrections increases. For a reciprocal aiming task, some of the MT increase occurs because the person spends more time in contact with each target to evaluate visual feedback and plan the movement to the next target.
- **Impulse-timing hypothesis.** Schmidt and colleagues (1979) proposed that many speed-accuracy tasks involve movements that are too fast to allow for the use of visual feedback to make corrections during the movement. In these situations, they hypothesized that a person programs commands in advance of movement initiation. These commands are forwarded to the muscles as "impulses," which are the forces produced during a specific amount of time. The result is that the arm is forcefully driven toward the target and achieves accuracy based on the specified amount of force and time. Because amounts of force and time relate to movement variability, increases in movement velocity result in more variable movement. To correct an inaccurate outcome, the person would need to slow arm speed on the next attempt.
- **Multiple submovements hypothesis.** Meyer and colleagues (1988, 1990) adopted elements of both the intermittent-feedback and impulse-timing hypotheses. They proposed that before initiating movement, the person programs an initial impulse, which is then executed. If the movement is accurate, nothing further is required. But if feedback during the movement indicates that the movement will be inaccurate, the person prepares and executes submovements that adjust the initial velocity. This process continues until the person produces an accurate movement. The number of submovements made relates to movement time and the target distance and width (see also Yao & Fischman, 1999).

Figure 7.2 illustrates the relationship of this phase to the two movement phases for performing the manual aiming skill of putting a key into a keyhole, which is an example of a skill in which the speed-accuracy trade-off occurs.

The *first phase* is the *movement preparation phase,* which begins when the person makes the decision to perform the skill involving a speed-accuracy trade-off. In this phase, the person uses vision to determine the regulatory conditions that characterize the environmental context in which the action will occur. For example, for the action of putting a key into a keyhole, the regulatory conditions would include the size, shape, and weight of the key and the size, location, and spatial orientation of the keyhole. These characteristics would specify the direction and distance of the limb movement as well as the accuracy demands of the situation. Together with other relevant information detected by the sensory system, such as the characteristics of the key that touch would provide, this sensory information would be transmitted to the CNS to prepare the specific movement characteristics to initiate and carry out the intended action.

Included in the movement preparation phase is the selection of a speed- or accuracy-based strategy to perform the skill. Recent fMRI evidence shows that the strategy selected activates different brain regions (Vallesi, McIntosh, Crescentini, & Stuss, 2012). This evidence provides an interesting level of support for the

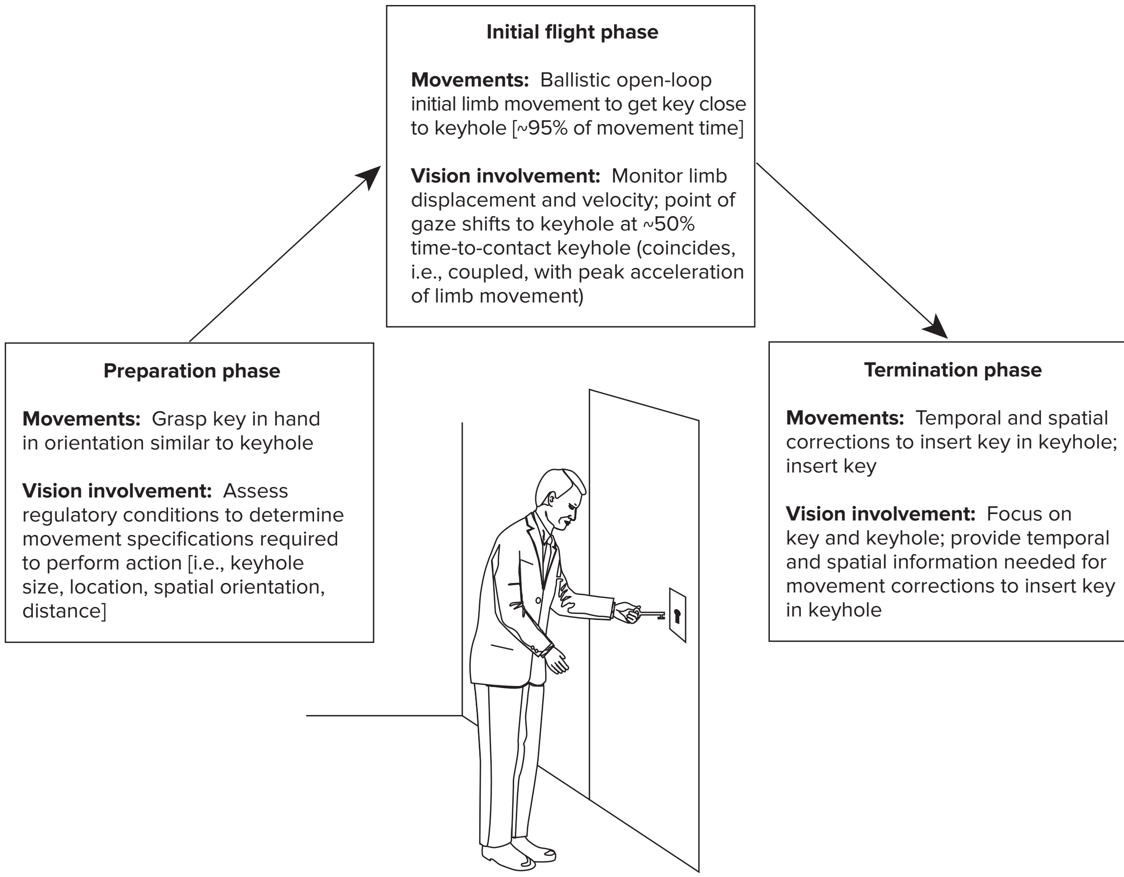

FIGURE 7.2 The three movement phases of putting a key in a keyhole in the lock on a door. In this figure, the use of vision is described to illustrate the role of an important source of sensory information in performing a manual aiming skill.

behavioral trade-off observed as different brain regions are involved in the preparation of the movement.

The *second phase* is commonly referred to as the *initial flight phase.* It includes the beginning of the limb movement in the direction of the target, which in our example is the keyhole. As you read in the preceding section, this movement is relatively fast (i.e., ballistic) and occurs without the influence of sensory feedback. Although vision plays a minor role in this phase, it acquires limb displacement and velocity information and acquires time-to-contact information that will be used later as the movement nears the target to make movement modifications. Researchers continue to debate the need for vision of the moving limb during this phase (see Elliott, Helsen, & Chua, 2001, for a discussion of the research concerning this issue).

The third phase is the *termination phase.* It begins just before and ends when the target is hit, which in our example is when the key is inserted into the keyhole. Vision of the limb and target are important in this phase so that movement accuracy information can be transmitted to the CNS and any needed movement corrections can occur to allow the person to achieve the action goal of hitting the target.

One final point to consider here is the way in which *vision and movement interact* in skills involving a speed-accuracy trade-off. Note that the intended action influences the way in which vision functions. In the three phases of the manual aiming task just discussed, the intent to put a key in a keyhole directs vision to focus on the keyhole itself, which provides during the movement preparation phase the critical regulatory conditions to which the movements will need to conform. Visual information during this phase also establishes the basis for the initial movement trajectory and velocity for moving the key toward the keyhole. During the termination phase, the action goal to put the key into the keyhole directs vision to detect speed and accuracy information that will allow precise movement adjustments to achieve the action goal.

PREHENSION

Prehension is the general term used to describe actions involving the *reaching for and grasping of objects.* Research evidence has shown that the movements involved in prehension consist of three distinct components: *transport, grasp,* and *object manipulation.* The object manipulation component refers to the functional goal for the prehension action. This means that an important part of understanding the control of prehension—unlike pointing and aiming movements—relates to what the person intends to do with the object after grasping it. The importance of this component is that it influences the kinematic and kinetic characteristics of the transport and grasp components. For example, if a person intends to pick up a cup to drink from it, the transport and grasp characteristics will differ from those associated with the person picking up the cup and moving it to a different location on a table (see Newell & Cesari, 1999, for a discussion of the motor control implications of this issue). In fact, it is because of the relationship of the object manipulation component to the other two components that prehension must be considered an action that is different from the action of reaching and pointing to an object.

To achieve the same object manipulation goal for a prehension action, people can use different movement characteristics to grasp the object.

A CLOSER LOOK

Using Movement Therapy to Improve Prehension and Other Upper Extremity Skills for Individuals with Hemiparesis

People with hemiparesis (i.e., partial paralysis on one side of the body) have difficulty using one arm, usually due to a stroke or other CNS disorder such as cerebral palsy. Two physical rehabilitation intervention strategies that have been shown to be effective as a treatment of upper-limb impairment for individuals with hemiparesis are called *constraint-induced movement therapy* (CIMT) and *hand-arm bimanual intensive therapy* (HABIT). The goal of both intervention therapies is to encourage the use of the impaired arm to perform tasks that the impaired arm should perform alone or together with the other arm. It is common for people with hemiparesis to eventually not use the impaired arm at all, a condition known as learned disuse.

The CIMT therapy, which was first introduced by Edward Taub and colleagues (see Taub, Crago, & Uswatte, 1998, for a review of the research and theory on which CIMT is based), involves constraining the unimpaired arm with a splint, cast, or sling and forcing the use of the impaired arm. The majority of the evidence supporting the efficacy of this treatment has come from patients with stroke, although more recent applications have been reported for children with cerebral palsy (CP) (see Gordon, Charles, & Wolf, 2005, for a brief review of this research).

The general protocol of CIMT: The therapy is an intensive procedure that requires the active participation of the patient and therapists for several hours a day for two weeks. Patients typically have their unimpaired hand restrained for 90 percent of their waking hours for fourteen consecutive days, during which they engage in six hours of intensive repetitive task practice and "shaping." Tasks include screwing and unscrewing bolts, picking up coins and moving them to specified locations, and so on. "Shaping" refers to practicing small parts of functional tasks and progressively increasing the complexity and difficulty of the parts until the actual functional task can be performed.

Effectiveness of CIMT: Numerous research studies have provided results that describe the effectiveness of CIMT, especially for improving and increasing the daily functional use of the impaired arm. (For a review of the history of the development of CIMT and research that has demonstrated its effectiveness, see Fritz, Butts, & Wolf, 2012.)

The HABIT therapy was first introduced by Andrew Gordon and colleagues (see Gordon, Schneider, Chinnan, & Charles, 2007, for a discussion of a randomized control trial of the therapy with children with hemiplegic cerebral palsy). It also involves intensive activity with the impaired arm performing bimanual tasks with the unimpaired arm.

The general protocol of HABIT: The intensive procedure followed by this therapy involves the use of both arms to engage in play and functional activities, which include both fine and manipulative gross motor skills, for 10 out of 12 days in a two-week period. A "shaping" approach, similar to CIMT, is also included.

Effectiveness of HABIT: The original randomized control trial study reported by Gordon et al. (2007) found improvements in hand-use assessments, and increased use of impaired arm and hand use, and overall bimanual hand use. Reviews of research since that report have provided support for the efficacy of the HABIT therapy (e.g., Klepper, Krasinski, Gilb, & Khalil, 2017).

The Relationship between Prehension Components

From a motor control perspective, prehension involves the arm transporting the hand to an object as the hand forms the grip characteristics that are needed to grasp the object. A motor control question of interest here concerns the relationship between the *transport and grasp components.* Although initial attempts to answer this question proposed that these components were relatively independent (e.g., Jeannerod, 1981, 1984), more recent evidence has established that these *two*

prehension the action of reaching for and grasping an object that may be stationary or moving.

A CLOSER LOOK

Relating Fitts' Law to Drinking from a Mug

In the experiment by Latash and Jaric (2002) the researchers studied how people grasp, pick up, and sip from a mug, just as they would do in everyday life. As part of this study, they developed a way to identify the index of difficulty (ID) that accounted for mug size and the amount of liquid in the mug. Instead of target size and distance, the accuracy characteristic of most tasks researchers have used to investigate Fitts' law, they considered the accuracy component of the task to be the transporting of the mug from a tabletop to the mouth without spilling its contents. Their logic was that a mug that is full to its rim requires more movement accuracy and is therefore a more difficult task than a mug that is less full. And, if consistent with Fitts' law, this task should require more movement time than transporting the mug that is less full.

Calculating the index of difficulty (ID): Four mugs of different diameters (3.2, 6.5, 8.5, and 10.0 cm) were filled with 6 or 7 levels of water beginning from 0.5 to 1.0 cm from the rim to a small amount on the bottom. The researchers calculated the ID for each mug size and water level by determining the ratio of mug diameter to the distance of the water level from the mug rim—that is, *mug diameter/water level distance (in cm) from the rim*. For example, the mug with a diameter of 10 cm that was filled with water to 1 cm from the rim had an ID of 10 (i.e., 10/1 = 10); the same mug filled to 6 cm from the rim had an ID of 1.67 (i.e., 10/6 = 1.67). The four mug sizes and water levels resulted in 16 IDs.

The relationship between ID and movement time (MT): When the participants' movement times (MTs) (from initial mug movement to initial mouth-mug contact) were compared for the 16 IDs, the results were consistent with the Fitts' law prediction that movement times would be fastest for the lowest IDs and slowest for the highest IDs.

Relating the results to the control of the coordination of many degrees of freedom: On the basis of the relationship between ID and MT, as well as other movement-related measures (head angle, mug tilt angle, and head position), the researchers concluded that "ID could be viewed as a significant parameter that reflects task constraints within the natural movement of taking a sip from a mug" (p. 147). In terms of the nervous system's control of the coordination of hand, arm, and head movements required to perform this task (which represents the control of many degrees of freedom), this conclusion means that the ratio of the mug diameter to the distance of the contents from the rim directly influences the nervous system's spatial and temporal organization of the appropriate coordination elements to allow a person to drink from a mug without spilling its contents.

components are temporally coupled and interact synergistically (i.e., cooperatively) according to task demands. This means that although the reach and the grasp are two separate movement components, they function in an interdependent manner.

The most compelling evidence demonstrating this coupled relationship has come from movement analyses of the fingers and thumb as the hand moves toward the object. For example, in their highly influential research Jakobson and Goodale (1991) showed that the object's size and distance from the hand influenced the timing of when the distance between the fingers and thumb (i.e., grip aperture) reaches its maximum during the transport component of the reach. Interestingly, they, along with others (e.g., Chieffi & Gentilucci, 1993; Hu, Osu, Okada, Goodale, & Kawato, 2005; Volcic & Domini, 2016), found that *regardless of object size and distance, maximum grip aperture and hand closure occurred at approximately two-thirds of the total movement time duration* of the action. More conclusive support for the temporal coupling of hand transport and grip aperture was provided by researchers who presented a mathematical model that can predict this temporal relationship for any hand transport duration (Hu et al., 2005). As is consistent with the research just described, this model shows that the maximum grip aperture occurs when the hand is approximately two-thirds through the total time duration of the reaching movement.

In addition, research evidence has shown that the kinematics of both the transport and grasp components are modified when the object is suddenly and unexpectedly moved during the transport phase (e.g., Gentilucci, Chieffi, Scarpa, & Castiello, 1992), and when an obstacle needs to be avoided to get to the object (e.g., Saling, Alberts, Stelmach, & Bloedel, 1998). These kinematic changes give additional support to the conclusion that there is a strong *temporal coupling* between the reach and grasp components of a prehension action. Thus, prehension serves as an additional example to those described in chapter 5 of how muscles and joints involved in a complex action cooperate synergistically as a *coordinative structure* to enable people to achieve an action goal in a variety of situations.

The Role of Vision in Prehension

Prehension actions are a type of speed-accuracy skill because accurate hand movement is required and the movement speed will be influenced by that accuracy demand. As a result, we should expect to find that vision is involved in prehension actions in ways that are similar to those we discussed in the preceding section on speed-accuracy skills. In fact, this is the case, with one exception. The exception involves the object manipulation component of prehension actions.

Consistent with its role in the speed-accuracy skills we discussed previously, vision assists the planning of prehension actions by providing information about the regulatory conditions of the environmental context. Together with the person's intended use of the object, the regulatory condition information is transmitted to the CNS, which then prepares "ballpark" estimates of the spatial and temporal characteristics for the transport and grasp components of the reaching movement. Evidence for the importance of visual information about object properties in this CNS planning activity was provided in a study that required participants to reach and grasp a variety of different objects (Verhagen, Dijkerman, Medendorp, & Toni, 2012).

Vision next plays an essential role as the hand travels toward the object by detecting when the hand will contact the object so that the timing of the grip aperture can be controlled appropriately. It also provides information about the spatial characteristics of the grip relative to the object's size, shape, and orientation so that the spatial characteristics of the grip can be controlled appropriately. Visual feedback related to these movement characteristics will be used by the CNS to modify movements as needed to allow achievement of the prehension action goal. In fact, research has shown that grasp characteristics are negatively affected when a person cannot see the object during the initial portion of the transport phase (Fukui & Inui, 2006). Unlike the speed-accuracy skills we discussed earlier, vision monitors the grasp itself to supplement tactile and proprioceptive feedback to ensure that the grasp adjusts as needed during the grasping and manipulation of the object. And, as Volcic and Domini (2016) found, grasping movements are "smoothly and automatically adjusted to the current visual feedback. . ." (p. 2174) even when it might be more advantageous to disregard the visual feedback and rely only on the haptic feedback.

As you read in chapter 6, binocular vision enhances the performance of prehension actions, especially in terms of the preparation of grip size and force (Jackson, Newport, & Shaw, 2002). In addition, research by Brown, Halpert, and Goodale (2005) has shown that because of the different roles of central and peripheral vision, especially as they relate to the two visual systems of vision-for-perception and vision-for-action, prehension skill performance is enhanced when the person looks directly at the object. This directing of the point of gaze at the object allows the two visual systems to optimally function during the prehension action.

Prehension and Fitts' Law

One final point that is important to note with regard to the motor control aspects of prehension is that it demonstrates speed-accuracy trade-off characteristics. In fact, researchers have established that Fitts' law consistently applies to prehension for both laboratory tasks and activities of daily living. For example, in an experiment by Bootsma, Marteniuk, MacKenzie, and Zaal (1994), movement distance and object width influenced movement time during prehension in accordance with the predictions of Fitts' law. In addition, these object characteristics influenced the movement kinematics of the action. The relevance of the kinematic evidence is that it provides a way

A CLOSER LOOK

Prehension Situations Illustrate Motor Control Adaptability

An experiment by Steenbergen, Marteniuk, and Kalbfleisch (1995) provides a good illustration of how adaptable the motor control system is. We see this adaptability when people alter movements of a specific action to accommodate characteristics of the task situation. The authors asked the participants to reach and grasp with the right or left hand a Styrofoam cup that was either full or empty. Participants had to grasp the cup, located 30 cm in front of them, then place it on a round target 20 cm to the right or left. Movement analyses of the hand transport and grasp phases revealed interesting differences at the movement level depending on which hand a person used and whether the cup was full or empty. For example, during the transport phase, hand velocity was distinctly faster and peak velocity was earlier when the cup was empty. The grasp aperture time also varied according to the cup characteristic. Maximum grasp aperture occurred earlier in the transport phase for the full cup, a situation demanding more movement precision. In terms of coordination of the joints involved in the action, participants froze the degrees of freedom of the shoulder, elbow, and wrist joints during the prehension movements for both full and empty cups. However, when the cup was full, participants increased stabilization during the movement by making a trunk postural adjustment that moved the shoulder forward.

to explain why movement time increases as object width decreases. The kinematics showed that as objects decrease in size, the amount of time involved in the deceleration phase of the movement increases, suggesting that the increase in movement time associated with the smaller objects is due to the person reducing the speed of the limb as it approaches the object. This means that when a person reaches for a cup that has a small handle, not only will the transport and grasp kinematics differ from reaching for a cup with no handle, but the movement time will also be slower, because of the increased accuracy demands of grasping the small handle.

A different approach to relating prehension actions to Fitts' law was reported by Latash and Jaric (2002). They developed a way to identify an index of difficulty that would account for the size of a mug and the amount of liquid in it. They reasoned that reaching, grasping, and drinking from a mug demands accuracy in a way that should influence arm movement speed as well as coordination of the limb segments involved, which means that Fitts' law should apply. But the accuracy component for this type of task is different from manual aiming tasks. Drinking from a mug, or any container, involves not only the size of the container or handle, but also how full it is. This is because the movement involved is transporting the container from its location to the person's mouth without spilling the contents. In their experiment, the researchers developed a ratio of mug size and water level that calculated an index of difficulty, which like Fitts' law predicted movement times from initial mug movement to the drinker's mouth.

Implications for Practice

From an applied perspective, the motor control research evidence about prehension has important implications for the development of practice conditions to help people improve their prehension capabilities. Because of the cooperative relationship between the reach, grasp, and object manipulation components, it is essential that prehension practice or therapy strategies involve functional activities (e.g., Wu, Trombly, Lin, & Tickle-Degnen, 1998 Winstein, Wulf, & Schweighofer, 2015). In addition, because movement characteristics of reach and grasp components interact in various ways according to object characteristics, it is important that practice involve reaching, grasping, and manipulating a variety of object characteristics and manipulation goals. Finally, because of the interdependent relationship of the components of prehension, it would not be beneficial to separate the reach, grasp, and object manipulation goal so that a person could practice each component separately. It is worth noting that researchers in Australia have incorporated

A CLOSER LOOK

A Handwriting Demonstration of Motor Equivalence

Write Your Signature

1. with a pen in your preferred hand.
2. with a pen in your nonpreferred hand.
3. with a pen held in your mouth by your teeth.
4. with your preferred hand on the chalkboard.

Compare the Spatial Characteristics of the Four Handwriting Samples

1. Describe the similarities you see.
2. Describe the differences you see.

Undoubtedly, specific elements of your signature remained constant regardless of which muscle groups were involved in the writing action. Your ability to engage various muscle groups to write your signature demonstrates how the act of handwriting illustrates the concept of motor equivalence. Variations of this demonstration have been reported by researchers since the 1940s (e.g., Lashley, 1942; Raibert, 1977).

these suggestions for developing a virtual reality system designed to improve reaching and grasping skills for traumatic brain-injured people. The system (called Elements) engages participants in a variety of movements to various shapes, sizes, and locations of virtual objects (Mumford et al., 2012).

HANDWRITING

Investigation of the control mechanisms responsible for handwriting is a prominent theme in the study of motor control (see Bullock, 2004). Researchers generally agree that different control mechanisms are involved in controlling *what people write* (letters, words, numbers, etc.) and *how they write it* (the writing strokes producing the letters, words, etc., on the writing surface).

When we consider the act of handwriting from an anatomical perspective, we see that there is a great deal of individual variation in terms of limb segment involvement. But when researchers obtain handwriting samples from one person, they offer strong evidence for what Bernstein (1967) referred to as **motor equivalence**. That is, a person can adapt to the specific demands of the writing context and adjust size, force, direction, and even muscle involvement to accommodate those demands. The notable outcome is that there is a great degree of similarity in characteristics such as letter forms, writing slant, relative force for stroke production, and relative timing between strokes. People have little trouble varying characteristics such as movement time and writing size, among others.

The complexity of handwriting control makes it difficult to develop a simple control model describing the components of this process. A person can write his or her signature or a familiar phrase with the preferred hand, with the nonpreferred hand, with a foot, or by holding a pen in the mouth. This suggests that at least the spatial features of writing are represented in the memory system in an abstract form. Also, this motor equivalence capability suggests the involvement of coordinative structures in handwriting control.

Another interesting feature of the act of handwriting is that several control processes occur at the same time. To write a sentence, a person must use lexical and semantic cognitive processes, as well as motor control processes. Writing requires the person to retrieve words from memory. These words must have meanings that fit what the writer intends to convey. The written sentence requires specific grammatical construction. The words require a certain spelling, which involves the person's movement of the limb to produce specific letters that are of an appropriate size and shape for what he or she is writing on. Further,

motor equivalence the capability of the motor control system to enable a person to achieve an action goal in a variety of situations and conditions (e.g., writing your signature with either hand).

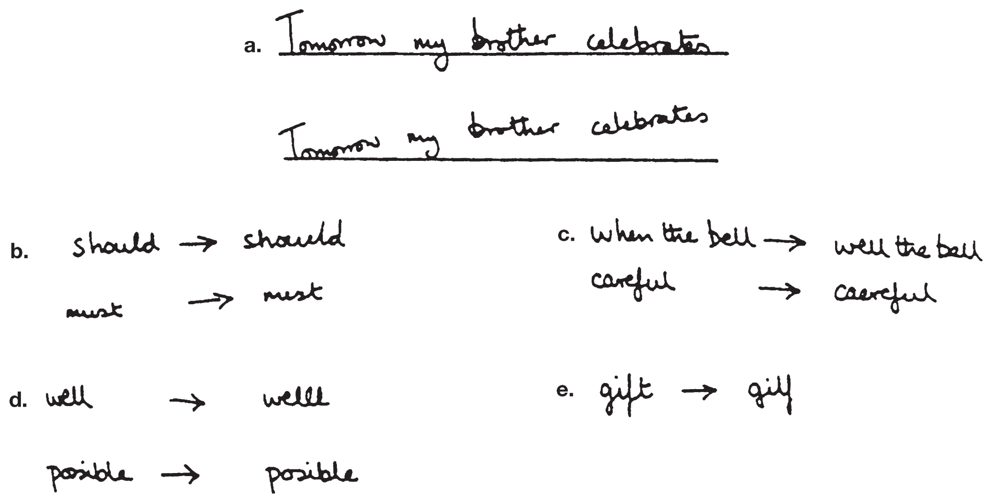

FIGURE 7.3 Handwriting examples from the experiment by Smyth and Silvers showing errors related to writing without vision available [bottom line in (a); right side of arrows in others] as compared to writing with vision available. (a) Shows errors as deviating from the horizontal; (b) shows errors as adding and deleting strokes; (c) shows adding and deleting of letters; (d) shows adding or deleting of repetitions of double letters; (e) shows reversing of letters. *Source:* From Smyth, M. M., & Silvers, G. (1987). Functions of visions in the control of handwriting. *Acta Psychologica, 65*, 47–64.

the individual must hold the writing instrument with an appropriate amount of force to allow these letters to be formed. The capability of humans to carry out these various cognitive and motor elements in relatively short amounts of time demonstrates both the complexity and the elegance of the control processes underlying the act of handwriting.

Vision and Handwriting

A substantial amount of research evidence indicates that vision plays an important role in the control of handwriting actions. One of the best demonstrations of this role was provided by Smyth and Silvers (1987), who showed that a person who is asked to write with his or her eyes closed adds extra strokes to some letters, omits strokes from some letters, and duplicates some letters. And if visual feedback is delayed while a person is writing, that person makes many errors, including repeating and adding letters.

On the basis of their own research and that of others, Smyth and Silvers proposed that vision performs two distinct functions in the control of handwriting. One function is to help the writer *control the overall spatial arrangement of words on a horizontal line.* We see an example of this function in figure 7.3, where handwriting samples taken from people writing without vision available show distinct deviations from a horizontal line. The second function for vision is to help the writer *produce accurate handwriting patterns,* such as the appropriate strokes and letters required for the written material. Again, evidence of this is seen in figure 7.3. People who wrote without vision available added or omitted strokes, added extra letters, deleted letters, and reversed letters.[1]

BIMANUAL COORDINATION SKILLS

In addition to unimanual coordination skills, people perform many motor skills that require the simultaneous performance of the two arms, that is, **bimanual co-ordination**. Sometimes the two limbs do essentially the same thing (*symmetric bimanual coordination*); this occurs when someone rows a boat or when a person in a wheelchair rolls the wheels

[1]For a review and synthesis of research addressing the roles of various types of sensory feedback in handwriting, see Danna and Velay (2015).

of the chair in order to go straight forward or backward. But more interesting from a motor control perspective are *asymmetric bimanual coordination* situations in which each limb must do something different. For example, a guitar player holds strings with one hand to determine chords, while plucking or striking strings with the other hand to produce sound. A skilled drummer can produce one rhythm with one hand while producing another with the other hand. The serve in tennis requires the player to toss the ball into the air with one arm while moving the racquet with a very different movement pattern with the other. And unscrewing the cap from a jar requires each hand to perform different movements because one hand holds the jar.

Bimanual Coordination Preferences

An intriguing question about the performance of bimanual coordination skills is this: *Why is it more difficult to perform skills that require asymmetric than symmetric bimanual coordination?* For example, why is it difficult to rub your stomach with one hand while at the same time tapping the top of your head with the other hand? This task is clearly more difficult to perform (especially the first time you try it) than doing the same movements with each hand. The answer to this question is based on an important characteristic of the motor control system: its inherent preference for controlling limb movements; it prefers symmetry. For the two arms, this means that the two limbs *prefer* to do the same thing at the same time. This preference helps the performance of symmetric bimanual skills, but can lead to problems for asymmetric skills.

The earliest research to demonstrate the motor control system's preference to coordinate the two arms to move together involved the simultaneous performance of discrete movements. In what is now seen as a classic series of experiments, Kelso, Southard, and Goodman (1979) had people perform rapid aiming movements simultaneously with each arm to targets that had the same or different Fitts' index of difficulty (ID) values. Results showed a *temporal basis* for the coordination of the two arms as they moved with similar movement times not only to two targets with the same ID values, but also to two targets that had different ID values.

In the bimanual coordination task just described, the *more difficult* (according to the Fitts' law definition) of the two aiming tasks influenced the performance of the arm doing the less-difficult task. That is, the arm that was required to move a shorter distance (i.e., the less-difficult task) slowed down in comparison to when it moved the same distance alone. Similar results have been shown when *task complexity* differences characterized the bimanual coordination task. For example, the task used in an experiment by Swinnen, Schmidt, Nicholson, and Shapiro (1990) required participants to rapidly move their arms in different spatial-temporal patterns. The task involved moving one arm in a simple one-direction arm-flexion movement while at the same time moving the other in a two-part flexion and extension movement. Both arms were to complete their movements in a movement time of 800 msec. At the beginning of practice, participants generally produced with each arm the similar movement patterns, which typically resembled the more complex two-part movement required by one arm.

Motor Control of Bimanual Coordination

Researchers are not certain how bimanual coordination is controlled. At present, we know that the two arms are coupled into a coordinative structure that prefers spatial-temporal symmetry. And an in-phase relationship between the arms (i.e., both arms flexing and then extending at the same time) appears to be the predominant symmetrical pattern. In addition, we know that with practice, a person can learn to uncouple (sometimes referred to as "dissociate") the two limbs and simultaneously move his or her arms asymmetrically. But, we do not yet understand the control mechanisms involved in this dissociation process. Some researchers (e.g., Verschueren et al., 1999a) report

bimanual coordination a motor skill that requires the simultaneous use of the two arms; the skill may require the two arms to move with the same or different spatial and/or temporal characteristics.

LAB LINKS

Lab 7b in the Online Learning Center Lab Manual for chapter 7 provides an opportunity for you to perform symmetric and asymmetric bimanual coordination tasks that will allow you to experience the intrinsic coordination characteristic of symmetric bimanual coordination even though the achievement of the action goal of the skill requires asymmetric bimanual coordination.

evidence that *proprioceptive feedback* is important in this process, while others (e.g., Mechsner, Kerzel, Knoblich, & Prinz, 2001) propose that *visual feedback* is the basis for performing the complex asymmetric bimanual coordination. (See Shea, Buchanan, & Kennedy, 2016, for a more recent review of research related to this issue.)

Motor control theories have inspired two distinct views on how people learn to uncouple their limbs. Those who support the motor program theory argue for generalized motor program involvement, but there is disagreement about whether two new generalized motor programs develop so that each arm becomes controlled by a separate program or whether one generalized motor program develops in which each arm can perform somewhat independently. From a dynamical systems theory perspective, the control issue is rather straightforward. The initial tendency for the arms to be spatially and temporally coupled represents an attractor state characterized by a specific relative phase relationship. But, with practice, the stable pattern is destabilized and a new attractor emerges as the new pattern becomes stabilized. (See Boyles, Panzer, & Shea, 2012; Oliveira & Ivry, 2008; and Shea, Buchanan, & Kennedy, 2016, for more in-depth discussions of the motor control of bimanual movements.)

Implications for Practice

Teachers, coaches, and therapists who are aware of bimanual coordination tendencies will recognize the need to give special attention to people who are learning skills that require the arms to perform different spatial-temporal movement patterns. The required unlinking of bimanual movements can be a difficult process for people. But, as both experience and research evidence (e.g., Kovacs, Buchanan, & Shea, 2010; Lee, Swinnen, & Verschueren, 1995; Swinnen et al., 1990; Walter & Swinnen, 1994) tell us, people can achieve success in performing these types of skills when they receive appropriate instruction, feedback, and practice. We will consider some of the strategies practitioners can use to facilitate the learning of asymmetric bimanual coordination skills in Units V and VI.

CATCHING A MOVING OBJECT

In many ways, catching an object is like the prehension action discussed earlier. However, there are two important differences. First, catching involves intercepting a moving object; prehension typically involves a stationary object. Second, the grasp of the object in the catching action ends the action; prehension typically involves doing something with the grasped object. Although in some sport situations, such as baseball and softball, there are occasions in which a player must remove the ball from the glove after the catch and throw the ball, this situation is uniquely sport and situation specific and will not be included in this discussion of catching.

Three Phases of Catching an Object

To catch an object, the person must first move the arm and hand toward the oncoming object. Then, he or she must shape the hand to catch the object. Finally, the fingers must grasp the object.

Williams and McCririe (1988) provided research evidence demonstrating the phases of catching with their study of 11-year-old boys trying to catch a ball with one hand (figure 7.4). A movement analysis of the catching action showed the following sequence. There was no arm motion for the first 160 to 240 msec of the ball flight. Then, elbow flexion gradually began and continued slowly and uniformly for about 80 percent of the ball flight. At about the same time, the fingers began to extend. The hand began to withdraw from the oncoming ball until about one-half of the ball flight time had elapsed. Then the upper arm accelerated about the shoulder, which resulted in the hand's being transported to the spatial position required

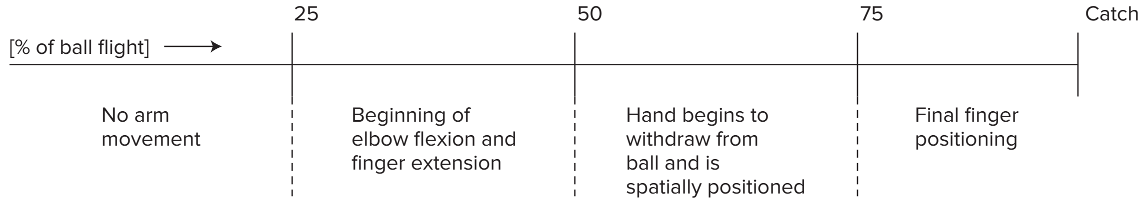

FIGURE 7.4 The arm, hand, and fingers movement characteristics involved in catching a ball in relation to the percentage of ball flight time. *Source:* Data from Williams & McCririe (1988). *Journal of Human Movement Studies, 14,* 241–247.

for intercepting the ball. Boys who caught the ball began final positioning action 80 msec earlier than boys who failed to catch it. By the time 75 percent of the ball flight was complete (113 msec prior to contact), each successful boy had his hand and fingers in a ready state for catching the ball.

These results indicate that vision provides advance information enabling the motor control system to *spatially and temporally set the arms, hands, and fingers before the ball arrives* so that the individual can catch the ball. It is especially noteworthy here that the person bases the grasping action on visual information obtained *before* the ball actually makes contact with the hand, rather than on feedback obtained after the ball has hit the hand. The extent of involvement of proprioception during pre–ball contact stages is not well understood. However, we know that proprioceptive and tactile feedback become involved after contact because the catcher needs to make adjustments to the grasp. Research evidence also shows that both central and peripheral vision operate when a person picks up information critical to catching an object.

Vision of the Object and Catching

Catching an object, such as a ball, is a complex perception-action skill that has challenged researchers in their efforts to understand how the visual and motor control systems interact. The results of these research efforts have identified several factors that influence successful catching which relate specifically to the visual observation of the object.

Amount of visual contact time. One factor is the amount of time of visual contact with the moving object. Research evidence indicates that constant visual contact is needed during two critical periods of time in the object's flight: the initial part of the flight and the period of time just prior to contact with the hand(s). How much time is required during each of these time periods has not been established, and undoubtedly depends on the situation.

Some researchers have reported evidence indicating that observation of the initial flight should continue until the ball reaches its zenith (Amazeen, Amazeen, Post, & Beek, 1999), although others have indicated that only the first 300 msec of flight are important (e.g., Whiting, Gill, & Stephenson, 1970). The important point here is that visual contact with the object is needed for an amount of time during its initial flight phase that is sufficient to obtain information to determine estimates of the direction and distance of the flight. (See Lopez-Molinar et al., 2010, for more recent evidence to support this point.)

In terms of visual contact with the object during its final portion of flight, research evidence indicates that the time period between 200 and 300 msec before hand contact is critical for successful catching (Savelsbergh, Whiting, Pijpers, & van Santvoord, 1993), although the precise amount of time may depend on the specific characteristics of the situation, especially the length of time the object is in flight and its velocity (see Bennett, Davids, & Craig, 1999). The need to see the ball during the final portion of its flight is to obtain specific time-to-contact information for the final spatial positioning of the hand and fingers, and the timing of the closing of the fingers during the grasp of the object.

What about visual contact with the object in flight between these two time periods? Research by Elliott and his colleagues (e.g., Elliott, Zuberec, & Milgram, 1994) indicates that continuous visual contact with the ball during this period of time is *not* essential. The Elliott et al. (1994) study showed that

LAB LINKS

Lab 7c in the Online Learning Center Lab Manual provides an opportunity for you to compare catching a ball when you can and when you cannot see your hands.

people can catch a ball that has a flight time of 1 sec by *intermittently seeing brief "snapshots"* (approximately 20 msec) of the ball every 80 msec of its flight. Thus, people can use visual samples of ball flight characteristics to obtain the information they need to catch the ball. This capability to use intermittent visually detected information to catch an object helps us understand how an ice hockey goalie can catch a puck or a soccer goalkeeper can catch a ball even though he or she must visually track it through several pairs of legs on its way to the goal.

Tau ***and catching.*** Another important motor control question concerning vision of the object and catching is this: Does the motor control system use the visual variable *tau* to enable people to catch an object? Although there is considerable debate about the answer to this question (see Caljouw, van der Ramp, & Savelsbergh, 2004, for a more complete discussion of this issue), a significant amount of research evidence indicates that *tau* is involved in solving the time-to-contact problem when catching an object, although *tau* alone does not appear to be sufficient to explain vision's role in catching (Mazyn, Lenoir, Montagne, & Savelsbergh, 2004).

When an object moves directly toward a person, the projected size of the object on the retina expands at a non-linear rate as the object approaches. The object expands more slowly when the object is farther away but increases its rate of expansion as it gets closer. It is this rate of expansion of angular size, which is often referred to as *looming,* that the visual system uses to determine when collision of the object with the person will occur. For the action of catching, this optical expansion establishes *when* the movement must be initiated and how quickly it must be completed to catch the object. For objects that do not move directly toward the person but require the person to run to catch them, *tau* also provides the visual basis for timing the catch, although the mathematics for calculating *tau* are distinctly more complex.

Vision of the hands and catching. An important question related to catching is this: *Must a person be able to see his or her hands throughout the flight of a ball to successfully catch the ball?* In one of the first experiments investigating this question, Smyth and Marriott (1982) attached a screen to the participants so they could see the oncoming ball, but not their hands. When the participants were able to see their hands, they averaged 17.5 catches out of 20 balls thrown. However, when they could *not* see their hands, they were able to catch an average of 9.2 balls out of 20. More important, when they could *not* see their hands, participants typically made a hand-positioning error: They could not get their hands into the correct spatial position to intercept the ball. But when they could see their hands, their typical errors involved grasping: They initiated too early the finger flexion they needed to grasp the ball.

Interesting as the Smyth and Marriott results may be, research since their work has shown that *experience* is an important factor influencing a person's catching success when he or she cannot see his or her hands. We might expect this, as Davids (1988) argued, because the effective use of peripheral vision is a function of age and experience. Because we use peripheral vision to see our hands as we try to catch an oncoming object, it is logical to expect that our need to see our hands to catch a ball will depend on our age and experience.

Fischman and Schneider (1985) provided empirical evidence that supports the influence of experience. Using the same experimental procedures as those of Smyth and Marriott, they included participants who had at least five years' experience in varsity baseball or softball. The results of this experiment (figure 7.5) showed that although the number of catches decreased when the experienced people could not see their hands, the type of error did not depend on whether or not the participants could see their hands. However, for the inexperienced ball catchers, more positioning errors than grasp errors occurred when they could not see their hands.

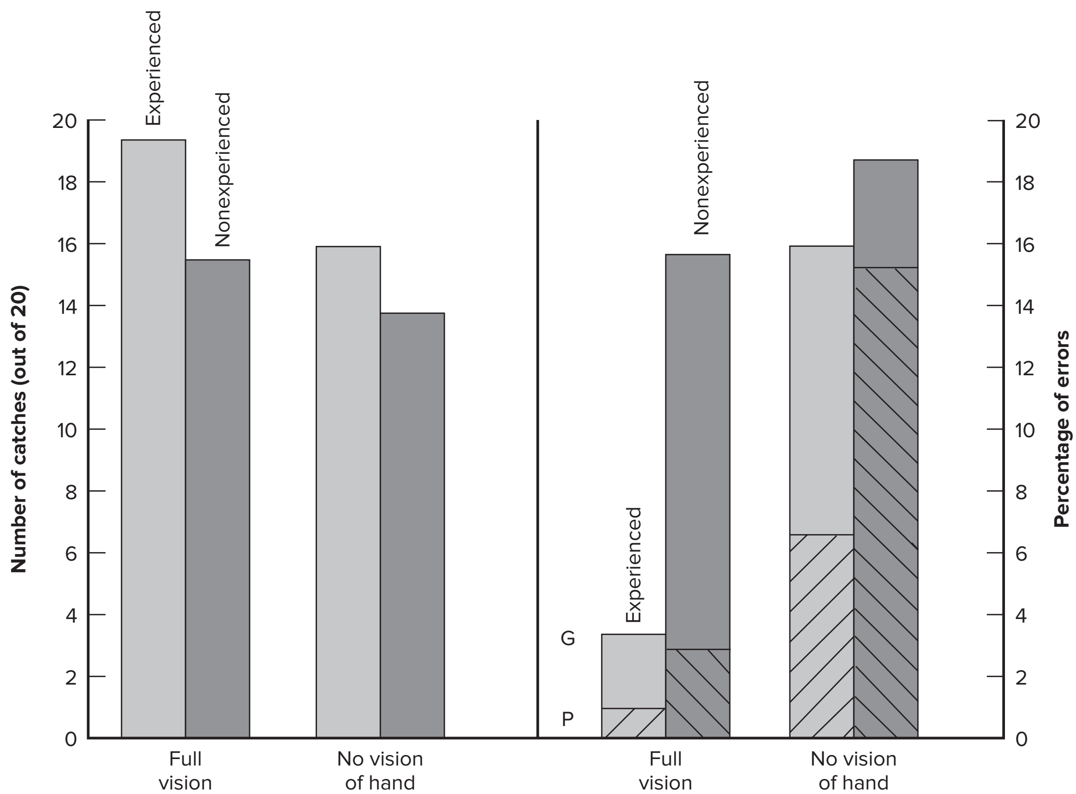

FIGURE 7.5 Results of the experiment by Fischman and Schneider showing the number of right-hand catches made (out of 20 chances) for experienced softball/baseball players and nonexperienced subjects and the percentage of errors made (based on 360 attempts) by each group that were classified as positioning (P) or grasp (G) errors when subjects either could or could not see their hands. *Source:* Data from Fischman, M. G., & Schneider, T. (1985). Skill level, vision, and proprioception in simple one-hand catching. *Journal of Motor Behavior, 17,* 219–299.

Researchers now generally agree that both ball catching experience and skill level influence the need for a person to see his or her hands while catching a ball (see Bennett, Davids, & Craig, 1999). More-experienced and skilled catchers do not need to see their hands; less-experienced and low-skill catchers require vision of their hands. The reason for this difference appears to relate to a person's capability to use proprioceptive feedback to catch a moving object. The less-experienced, low-skilled person needs visual feedback to assist in the use of proprioceptive feedback to spatially position his or her arms and hands and to effectively grasp the object. In terms of helping people improve their catching skill, this relationship between experience and the need for vision of the hands suggests that beginners and less-skilled people should practice catching primarily in situations where they can see their hands throughout the ball flight, from the point where the ball leaves the thrower's hand until the ball is grasped.

STRIKING A MOVING OBJECT

Like the action of catching a moving object, striking a moving object involves the spatial and temporal interception of an object. And, as we discussed for catching, the motor control of this action involves the coordination of movements that is influenced by vision in specific ways. Two experiments investigating the striking of a moving object illustrate how vision influences the control of this action.

A CLOSER LOOK

How Does a Person Catch a Ball That Requires Running to Catch It?

In many sports, players must run to catch a ball. A motor control question concerning this situation that has intrigued scientists for many years is this: *What control strategy does a person use to catch a ball that requires running some distance to catch it?* This question has generated interest because people seem to be able to learn to successfully perform this skill relatively easily, which is evident when we observe how quickly children learn this skill. The primary approach taken by scientists to answer this question has been to develop mathematical models that identify the critical favors involved in this skill and describe how the motor control system manages these factors.

The mathematical models identify two angles of two triangles as the critical factors involved in this catching situation (see McLeod, Reed, & Deines, 2001). These triangles and the angles are shown in figure 7.6.

- *Triangle 1* involves the ball flight and the fielder's position. Within this triangle, the critical angle is the angle of elevation of the fielder's point of gaze above the horizontal (angle α). This angle is created by a line from the ball location in the air at any moment to the fielder's position on the ground at that moment and a line from the fielder's position to the location on the ground directly under the ball.
- *Triangle 2* involves the ball flight, the ball projection point, and the fielder's position. Within this triangle, the critical angle (β) is the angle created by a line from the ball projection point to the fielder's position and a line from the fielder's position to the location on the ground directly under the ball.

Research based on this type of mathematical model has resulted in some general agreement with Chapman's (1968) original model for the catching situation in which the person must run straight forward or backward. However, there is no consensus among scientists for the situation in which the person must run to the side to catch the ball.

- *To catch a ball that requires running directly forward or backward,* angle α is the primary angle involved because the fielder's position would be along A_2 and its extension. Fielders time their arrival at the ball by running forward or backward at a speed that maintains α between 0° and 90°.
- *To catch a ball that requires running to the side,* both angles α and β are critical. As in the situation in which the fielder must run forward or backward, fielders time their arrival at the ball by running forward or backward at a speed that maintains α between 0° and 90°. However, researchers do not yet know why fielders choose the spatial path they follow to make the catch, which involves the control of β.

McLeod, Reed, and Dienes (2001) summed up the status of our current knowledge about the issue of how people run to catch a ball by saying: "We understand how α is controlled but not β" (p. 1355). Regardless of how this issue is resolved, the important point in terms of the discussion in this chapter is the critical involvement of the visual system. And vision appears to be involved in a way that requires little conscious control of the movements that must be executed to enable a person to achieve the action goal.

Vision and Baseball Batting

The classic experiment related to the role of vision in baseball batting was performed many years ago by Hubbard and Seng (1954). Using cinematography techniques, they found that professional baseball players tracked the ball only to a point, at which time they made their swing. This point did not coincide with the point where the bat made contact with the ball. Each batter tended to synchronize the start of the step forward with the release of the ball from the pitcher's hand. And, perhaps most important, the durations of the batters' swings were remarkably consistent from swing to swing, indicating that it was the initiation of the swing that batters adjusted according to the speed of the oncoming pitch. Interestingly, these findings agree precisely with expectations from a *tau*-based strategy for hitting. That is, the initiation of the batting action occurred at a critical time to contact.

A CLOSER LOOK

"Watch the Ball All the Way to Your Bat!"

A common instruction coaches give when teaching hitting in baseball is to tell players, "Watch the ball all the way to your bat." In light of this, it is interesting to note that research (e.g., Bahill & LaRitz, 1984) indicates that batters probably never see the bat hit the ball. If they do, it is because they have jumped in their visual focus from some point in the ball flight to the bat contact point. They do not visually track the ball continuously all the way to bat contact because this is virtually a physical impossibility. Batters commonly track the ball to a certain point and then visually jump to a point where they predict the ball will be at bat contact.

It is worth noting that more-skilled batters watch the ball for a longer amount of time than less-skilled players. Beginners tend to have the bat swing initiation movement influence their head position and "pull" their head out of position to see the ball/bat contact area.

From an instruction point of view, these characteristics suggest that *it is worthwhile* to instruct a person, "Watch the ball all the way to your bat." Even though the person can't really do that, this instruction directs the person's visual attention so that the person tracks the ball for as long as physically possible and keeps his or her head in position to see the ball/bat contact area.

Some of the findings of Hubbard and Seng have been either verified or extended in research reported since their study. For example, thirty years later, Bahill and LaRitz (1984) used more sophisticated technology to closely monitor eye and head movements of a major league baseball player and several college baseball players. The study was done in a laboratory situation that simulated players' responses to a high-and-outside fastball thrown by a left-handed pitcher to a right-handed batter. The major league player visually tracked the ball longer than the college players did. The college players tracked the ball to a point about 9 ft in front of the plate, at which point their visual tracking began to fall behind the ball. The major league player kept up with the ball until it reached a point about 5.5 ft in front of the plate before falling behind in his tracking. Also, regardless of the pitch speed, the major league player followed the same visual tracking pattern and was very consistent in every stance he took to prepare for the pitch. While tracking the ball, his head position changed less than one degree across all pitches but he never moved his body.

Batting also involves perception-action coupling, as demonstrated in research by Katsumata (2008). Two timing characteristics showed this coupling. First, as other researchers have reported, the timing of the initiation of stepping with the front foot and its associated weight shift was

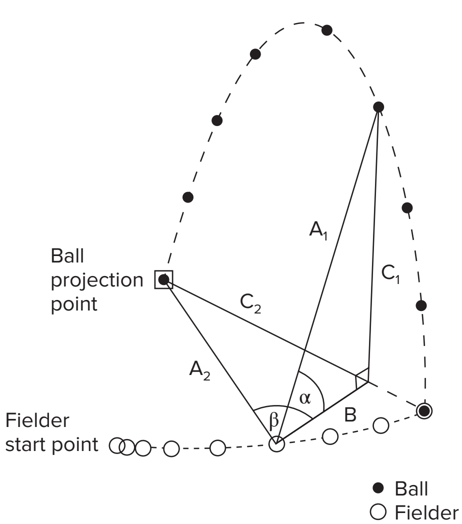

FIGURE 7.6 An illustration depicting the critical angles that McLeod, Reed, and Dienes propose the motor control system must manage so that a fielder can run and catch a ball. The filled circles represent the locations of the ball during its flight; the open circles represent the locations of the fielder who must run to catch the ball. The figure shows a ball hit to the fielder's right. To make the figure represent a ball hit along the line directly in front or behind the fielder, the lines that converge to form angles α and β (which are to the left of the final ball and fielder location) would converge to form these angles along line C_2 in front of or behind the final ball and fielder location. *Source:* Modified Figure 1, p. 1348 in McLeod, P., Reed, N., & Dienes, Z. (2001). Toward a unified fielder theory: What we do not yet know about how people run to catch a ball. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 1347–1355.

A CLOSER LOOK

General Vision Training Programs for Athletes: Do They Improve Sports Performance?

Bruce Abernethy and his colleagues at the University of Queensland in Australia have asserted for many years that although general vision training programs (e.g., Eyerobics) may help to improve certain basic vision functions, they do not improve sport-specific performance. Abernethy and Wood (2001) presented three lines of reasoning, all of which are supported by research evidence, as the basis for their position:

- Above-normal basic visual function (e.g., foveal and peripheral acuity, contrast sensitivity) does not favor elite athletes. A significant amount of research has shown that the visual advantage of elite athletes is sports-specific and perceptual in nature, that is, the interpreting and use of visual information to specific sports activities.
- Although many commonly measured visual functions can improve with training and repetitive practice, many of the reported improvements occur for people with visual defects. And, the exercises used to train specific visual functions are commonly procedures that are the same as, or similar to, the tests used to evaluate the functions.
- Experimental evidence is lacking to validate the effectiveness of general vision training programs for improving sports performance. In fact, in the experiment reported in this article, two visual training programs (Sports Vision and Eyerobics) led to performance improvements that were no better than reading about and watching televised tennis matches during the four-week training time, which consisted of four 20-min sessions each week.

influenced by the speed of the pitch; stepping initiation began later for slow pitches than for fast pitches. Second, the coordination of the timing of the initiation of the batter's moving his front foot forward and the initiation of swinging the bat was consistent regardless of pitch speed. Thus the temporal coupling of these events establishes a well-developed coordinative structure for the action of batting a pitched baseball.

Vision and Table Tennis Striking

In a study of five top table tennis players in the Netherlands, Bootsma and van Wieringen (1990, 2010) showed inconsistencies in the players' hitting movements because they were using online visual control. Players seemed to compensate for differences in the initiation times of their swings in order to hit the ball as fast and as accurately as possible. For example, when time to contact between the ball and paddle was shorter at swing initiation, players compensated by swinging more quickly. And evidence suggests that some of these players were making very fine adjustments to their swings while they were moving. Thus, whereas visual information may trigger the initiation of the swing and provide information about its essential characteristics, vision also provides online feedback information that the player can use to make subtle compensatory adjustments to the initiated swing.

LOCOMOTION

There is general agreement that at the nervous system level, *central pattern generators* (CPGs) in the spinal cord are involved in the control of human locomotion, which you will sometimes see referred to as gait (see Zehr & Duysens, 2004; Rossignol, Dubuc, & Gossard, 2006, and Ziskind-Conhaim & Hochman, 2017, for reviews of CPGs). These mechanisms provide the basis for stereotypic locomotive patterns such as walking and running. We can trace evidence for this spinal level of control to the work of the British Nobel laureate Sir Charles Sherrington and his colleagues at the end of the nineteenth and beginning of the twentieth centuries (e.g., Sherrington, 1906).

Using a procedure known as decerebration, which involves severing the brainstem and spinal

A CLOSER LOOK

Applying the Dynamical Systems View of Gait Control to Physical Therapy Interventions

We can see the involvement in locomotor control of dynamic interactions between the person and the environment in the effectiveness of a therapy strategy that helps reestablish normal rhythmic gait. Based on the dynamical systems control perspective, Wagenaar and van Emmerik (1994) recommended that therapists use various methods to help patients attain spontaneous production of the appropriate rhythmic structures for specific gait patterns by systematically altering gait speeds.

Wagenaar and Beek (1992) showed an example of the effectiveness of this procedure. They used a metronome to present rhythms to hemiplegic patients. When the authors systematically increased the rhythmic beat from 60 to 96 steps a minute, these patients improved the phase relationships of their arms and legs; this in turn positively influenced trunk rotation.

cord from the forebrain, Sherrington observed that decerebrated cats performed locomotor rhythmic muscular activity similar to that performed by intact animals. Later, Brown (1911) went a step further by additionally severing a cat's sensory pathways to the spinal cord; still, the cat showed rhythmic leg contractions appropriate for walking. More recent research (e.g., Grillner, 1981, 1985) has confirmed and extended these earlier observations (see Field-Fote, 2000, for an excellent overview of the spinal cord's role in the control of locomotion).

It is important to note that *CPG* is a term used to refer to a "functional network, generating the rhythm and shaping the pattern" of motor neuron activity (Zehr & Duysens, 2004, p. 348). For locomotion, the assumption is that we have at least one CPG per leg located in the spinal cord. Although research evidence supports a CPG-based control of human locomotion, there is also evidence that the CPG is not the sole basis for this control. Results from several studies have shown that proprioceptive feedback from muscle spindles and Golgi-tendon organs can influence locomotor movement patterns (see Zehr & Duysens, 2004, for an excellent review of this research, as well as clinical implications). For example, Dietz, Müller, and Colombo (2002) mechanically induced paraplegic and tetraplegic patients to produce stepping movements on a treadmill and found evidence from EMG recordings that afferent feedback from the hip joints was an important part of the locomotor activity. A different approach involved using the tendon vibration technique that was described in chapter 6, with healthy participants (Verschueren, Swinnen, Desloovere, & Duysens, 2003). The researchers showed that tendon vibration of specific leg muscles influenced EMG amplitude and muscle activity onset times for muscles involved in the swing and stance phases of walking.

The Rhythmic Structure of Locomotion

To understand how humans control the wide range of gait they are capable of, we must consider higher-level nervous system involvement, along with musculoskeletal dynamics and environmental interactions. The rhythmic structure of locomotor actions is an important characteristic that will serve to illustrate the roles of these various factors.

In the discussion in chapter 5 of the study by Shapiro et al. (1981), you saw that on the basis of an analysis of the four components of the Phillipson step cycle, walking and running each have a distinct rhythmic structure. In fact, this rhythmic characteristic is so common for walking and running gaits that mathematical models have been developed to describe their structures. Those who have developed these models view the leg movements in walking and running gaits as operating similar to a pendulum (see Wagenaar & van Emmerik, 1994; and Donker et al., 2001, for discussions about these models).

The rhythmic structure of gait patterns is not limited to leg movements. For example, when a person walks, distinct *rhythmic relationships exist between the movement of the arms and that* *of the legs,* and the specific character of this relationship relates to walking speed. Craik, Herman, and Finley (1976) first demonstrated this relationship by providing evidence that there are two arm-leg coordination patterns for walking: a 2:1 ratio (i.e., two arm swings to each leg stride) for very slow walking, and a 1:1 ratio for walking at speeds greater than 0.75 m/s (1.7 mi/hr, or 2.72 km/hr). Van Emmerik and Wagenaar (1996) reported that additional research has established that the transition from the 2:1 to the 1:1 arm-leg relationship occurs within the walking speed range of 0.2 to 1.2 m/s (0.5 to 2.7 mi/hr, or 0.3 to 4.32 km/hr). In addition to the arm-leg relationship, the pelvis and thorax also demonstrate a rhythmic relationship during walking. At lower speeds, they move in phase with each other, but out of phase at higher walking speeds.

What is the practical benefit of knowing about these various coordination characteristics of gait patterns? Van Emmerik and Wagenaar (1996) presented an excellent argument, along with research evidence, to support their view that knowing about these characteristics and using them as assessment techniques allow us to identify coordination problems in the trunk and extremities, especially for people with Parkinson's disease. For example, when walking at preferred speeds, Parkinson's patients show pelvis and thorax phase relationships that are exactly opposite to those described in the previous paragraph for healthy people.

Another example of the clinical use of coordination characteristics of gait patterns was presented in a study of people who recently had experienced anterior cruciate ligament (ACL) replacement surgery (Kurz, Stergiou, Buzzi, & Georgoulis, 2005). The researchers calculated the relative phase (a coordination quantification technique that was discussed in chapter 2) for the foot-shank and shank-thigh leg segments. The results showed relative phase characteristics for the ACL-reconstructed knee that differed from the normal knee. These differences led the researchers to conclude that the analysis of the relative phase dynamics of the reconstructed knee would provide clinically important information for patient performance at various stages of rehabilitation.

Another application of understanding the rhythmic coordination characteristics of gait is the use of this understanding to develop training or therapy strategies practitioners can use to help people improve their gait. For example, results from an experiment reported by Ford, Wagenaar, and Newell (2007) showed that post-stroke patients improved several aspects of their gait following treadmill training, with a metronome set at specific rhythmic frequencies (which systematically increased and decreased while the treadmill was at a constant speed), and with instructions to move their arms and legs to the beat of the metronome. The improvements included gait cadence, stride length, arm-leg swing coordination, and the phase relationship of the pelvic-thoracic rotation. (For a review of research concerning post-stroke interventions and gait control, see Hollands, Pelton, Tyson, Hollands, & van Vliet, 2012.)

Head Stability and Locomotion

When a person engages in locomotor activity, a goal of the motor control system is to *maintain head stability.* Researchers have demonstrated that head stability, as measured by the vertical orientation and minimal horizontal motion, is maintained during locomotor actions such as walking, walking in place, running in place, and hopping (for brief reviews of this research literature, see Cromwell, Newton, & Carlton, 2001; and Holt, Ratcliffe, & Jeng, 1999). In addition, researchers who have investigated the head stability characteristics of people walking at their preferred speed have found that the least amount of head movement in the vertical and anterior-posterior planes occurs at the preferred walking speed (e.g., Latt, Menz, Fung, & Lord, 2008).

Why is head stability so important to maintain during locomotion? The answer relates to the role the head plays. When we consider that the head contains the complex of sensory and motor ner-vous system components essential for us to navigate through an environment and maintain postural stability so that we don't fall, it becomes evident that head stability is important to maintain during locomotion. In addition, maintaining a stable head position during locomotion optimizes the use of vision in actions in which vision of an object while running is essential

Vision is critical to the control of locomotion over irregular terrain

Image Source

for achieving the action goal. For example, a baseball or tennis player must visually track the flight of the ball while running in order to catch or hit it. Finally, it is interesting in light of the importance of head stability during locomotion that researchers have found that children with cerebral palsy and adults with neurological impairment commonly adopt what could be considered "atypical" postural and gait characteristics as strategies to en-able them to maintain head stability while walking (e.g., Holt, Jeng, Ratcliffe, & Hamill, 1995; Holt, Ratcliffe, & Jeng, 1999).

Gait Transitions

Another important gait characteristic, which was briefly described in chapter 5, is the spontaneous change from a walking to a running gait (and vice versa) at certain speeds. Although these spontaneous gait transitions are common to all people, the speed at which transition occurs varies among individuals. Some people continue to walk at higher speeds than others, whereas some people continue to run at lower speeds than others. In addition, the walk-to-run transition typically occurs at higher speeds than the run-to-walk transition. (See DeSmet, Segers, Lenoir, & DeClercq, 2009, for a more indepth discussion about the kinematic characteristics of the walk-to-run transition, and for differences found for the transition on a treadmill compared to overground.)

Why do spontaneous gait transitions occur? Researchers have developed and tested several hypotheses to explain gait transitions (see Guerin & Bardy, 2008, for an overview of these hypotheses). The most prevalent of these has been that the transition occurs to minimize metabolic energy consumption (i.e., VO_2). Although researchers have provided evidence that supports this hypothesis, others have reported results that fail to support it (see Hreljac, 1993). At present, no single cause for gait transitions has been determined. Interestingly, Turvey et al. (1999) expressed doubts that a single cause can be identified because of the nature of complex biological systems. Kao and Ringenbach (2004) found evidence that supported the Turvey et al. conclusion by demonstrating that multiple factors, which may be specific to individuals, underlie gait transitions. (For an excellent review of determinants of gait transitions see Kung et al., 2018.)

Vision and Locomotion

In the preceding section, you saw that the control of locomotion depends on both proprioception and vision as sources of sensory information to augment and modify movement commands generated by the CNS. In this section we will look more specifically at the important roles that vision plays in two types of activities involving locomotion. As you will see, vision is more than a source of feedback; it also influences movement characteristics *before* action initiation.

A CLOSER LOOK

Gymnasts' Use of Vision While Walking on the Balance Beam

Shannon Robertson and her colleagues (e.g., Robertson, Collins, Elliott, & Starkes, 1994; Robertson & Elliott, 1996) have shown that skilled gymnasts use visual information as they perform their routines on a balance beam. In several studies, they involved gymnasts walking as fast as possible across a standard balance beam (5 m long × 10.5 cm wide). In the Robertson and Elliott (1996) experiment, nine female college varsity gymnasts performed the task with full vision, no vision, or distorted vision (goggles with a prism oriented vision to the left or right). Results for each condition were as follows:

	Amount of time to cross the beam	Number of times stepped off beam	Number of steps to cross beam	Number of form errors
Full Vision	3.0 sec	0.2	7	10
No Vision	4.0 sec	2.5	8	30
Distorted Vision	7.5 sec	8.4	9	42

The increase in form errors when the gymnasts had no vision or distorted vision was due primarily to deviations from an upright posture. These deviations resulted from the gymnasts' postural adjustments to maintain their balance as they walked.

Contacting objects. When you walk or run in your daily or sports activities, there are situations in which you must make contact with an object with one or both feet. For example, if you need to cross a street with a lot of puddles it is essential that your feet make contact with the dry areas among the puddles as you walk. In sports activities, baseball players must step on bases as they run, gymnasts performing the vault must contact the spring board with their feet at the end of the run-up, and long jumpers must step on the take-off board at the end of the run-up to the jumping area.

To discuss the motor control issues associated with making contact with objects with our feet during locomotor activity, we will use the long-jump situation as an example. It is an activity that many researchers have studied, with results that apply to other types of activities. To successfully perform the long jump, the athlete needs to make contact with the take-off board at maximum running speed. This run-up portion of the long jump can be thought of as similar to an aiming task; it requires the athlete to move a certain distance and then hit a target. The target is the take-off board, which is about 20 cm long (from front to back) and 1.2 m wide (from side to side). If any part of the athlete's foot extends beyond the back edge of the board (i.e., the edge nearer the landing pit), a foul is called and the jump does not count. On the other hand, if the tip of the foot strikes short of the board, the jump is that amount shorter because the jump distance is measured from the back edge of the board.

The motor control question related to the run-up is this: What does the athlete do during the run-up to hit the take-off board as accurately as possible? One possibility is that the athlete performs the same programmed step pattern during each run-up on each jump. This would mean that any error in hitting the take-off board would be due to an error in the programmed step pattern. However, research evidence has shown that this is *not* what the athlete does. Although each long jumper takes a number of steps during each run-up that is specific to him or her, the step lengths of the last few steps vary across run-ups. Most scholars now agree that the reason for this is that the athletes use visual information that specifies the amount of time it will take to contact the take-off board. The motor control system uses this *time-to-contact* information, which is specified by the visual variable *tau* (τ), to make stride-length adjustments during the last few steps to correct for the targeting error that has accumulated during the run-up. Without these adjustments, the athlete would either be short or long of the take-off board.

In what has become a classic experiment demonstrating this time-to-contact influence for a locomotor skill requiring object contact, Lee, Lishman, and Thomson (1982) filmed three highly skilled female long jumpers during their approaches to the take-off board. By analyzing stride-length changes as each athlete approached and contacted the take-off board for a series of six long jumps, the researchers observed several important gait pattern characteristics. We will examine these using the results from one of these athletes (an Olympic-level performer), presented in figure 7.7.

Initially, the athlete's stride length increased at a relatively constant rate for the first five to six strides; it then became similar for the next six strides. These strides were relatively consistent across the six jumps. Then, *on the final six strides,* something different occurred. The athlete made stride-length adjustments so that she could hit the board accurately. In fact, she made almost 50 percent of these adjustments on the last stride. The lower half of the figure shows why she had to make these adjustments. As the athlete ran down the track, small inconsistencies in each stride had a cumulative effect, so that when she was five strides from the board the error had risen to 37 cm. If she had not adjusted her stride lengths on the remaining strides, she would have missed hitting the take-off board by a long distance.

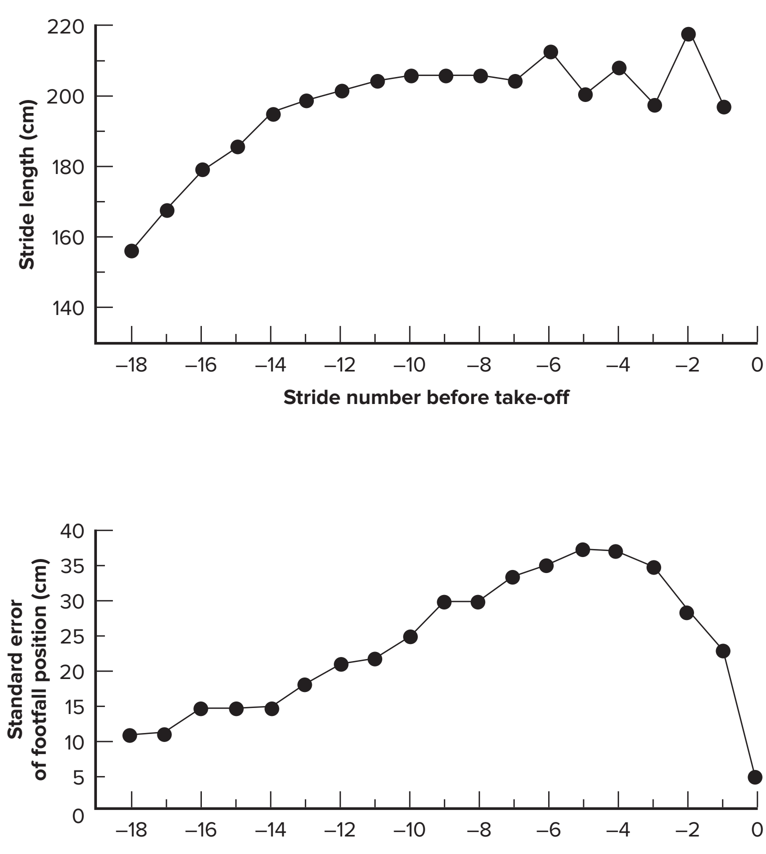

FIGURE 7.7 Redrawn from results of the experiment by Lee, Lishman, and Thomson showing the stride-length characteristics (top) and the standard errors for six long jumps by an Olympic-class female long jumper. *Source:* From Lee, D. N., Lishman, J. R., & Thomson, J. A. (1982). Regulation of gait in long jumping. *Journal of Experimental Psychology: Human Perception and Performance, 8,* 448–459.

A CLOSER LOOK

Visual Cues Can Aid Walking for People with Parkinson's Disease

One of the primary movement disorders common to people who have Parkinson's disease is slowness of gait (i.e., gait hypokinesia). Two questions have interested researchers and physical therapists concerning this gait problem. One, what movement characteristic accounts for the slowness? Two possibilities are cadence, which would mean that the difficulty relates to the rhythm, or beat, of the walking pace, and stride length, which would mean that the slowness is due to strides that are shorter than normal. The answer to this question is important for the second question: Is there a rehabilitation strategy that would help patients improve their control of walking gait speed?

To address these questions, Morris, Iansek, Matyas, and Summers (1994) compared walking gaits of Parkinson's patients with age-matched controls (60–85 years old) for instructions to walk along a 12-m walkway at "a comfortable pace" and at a "fast speed." *The results showed this:*

- *The Parkinson's patients walked more slowly than the control participants at both speeds, and had shorter stride lengths, but similar cadences.*

Then, the researchers provided visual cues to the Parkinson's patients by placing 50 cm by 5 cm laminated strips of cardboard on the walkway at intervals matching the mean stride lengths of the control participants for each speed. The patients were instructed to walk over each floor marker as they walked along the walkway. *The results showed this:*

- *The patients' velocity and stride lengths were similar to the controls for both speeds.*

The researchers concluded from their results that the regulation of stride length was the "key deficit" in gait slowness for patients with Parkinson's disease. And visual cues can be an effective rehabilitation strategy for helping these patients regulate gait speed.

Evidence that the improvement in these gait characteristics can be long-lasting was provided in a case study reported by Sidaway, Anderson, Danielson, Martin, and Smith (2006). The Parkinson's patient walked during a four-week training period with visual cues on the floor that were similar to those used in the Morris et al. (1994) experiment. At the end of the training period, the patient's stride length and gait speed improved. What was especially impressive, however, was that these improvements were maintained without the use of the visual cues one month after the training ended. More recent evidence of the visual-cueing benefit was presented by Vitorio et al. (2014). Also, for an extensive review of research on this issue, which showed a large amount of evidence to support the visual-cueing benefit, see Rocha et al. (2014).

In light of these results for visual cues, it is interesting to note that several researchers (e.g., Baker, Rochester, & Nieuwboer, 2007; McIntosh, Brown, Rice, & Thaut, 1997; see also a research literature review and meta-analysis by Ghai et al., 2018) have provided evidence to show the effectiveness of rhythmic auditory stimulation, which involves embedding a tone at specific intervals in music to provide a stepping pace for Parkinson's patients. Walking speeds can be varied by using music of different tempos.

These stride-length characteristics led the authors to describe the long jump run-up as consisting of two phases: an *initial accelerative phase,* where an athlete produces stereotypic stride patterns, followed by a *zeroing-in phase,* where the athlete modifies stride patterns to eliminate accumulated error. They concluded that a long jumper bases the correction process during the second phase on visual information obtained *in advance of* these strides. This means that the visual system picks up time-to-contact information from the board and directs the locomotor control system to make appropriate stride-length modifications for the strides remaining until contact with the take-off board.

It is worth noting that the use of visual time-to-contact information to regulate gait does not depend on the expertise of the person. Although the participants in the Lee and authors long jump study were highly skilled, novice long jumpers also have demonstrated similar stride-length adjustments consistent with the influence of *tau* (Berg, Wade, & Greer, 1994).

In the second phase of the run-up, the percentage of the total stride-length corrections made on each stride can be used as a way to demonstrate

A CLOSER LOOK

Avoiding Obstacles While Walking or Running

Research by James Cutting and his colleagues at Cornell University (e.g., Cutting, 1986; Vishton & Cutting, 1995) has shown that if a person is walking or running and wishes to maintain footspeed while avoiding an obstacle, three time periods are critical:

The Time Needed To

1. recognize that an object needs to be avoided;
2. adjust the footfall;
3. turn the foot to avoid the obstacle.

Of these three periods, the first is the most critical and takes up about 75 percent of the distance covered while the subject is approaching an object.

Implication for Clinical Rehabilitation and Sport
Because of the importance of early visual recognition of an object to be avoided, it is important to train people to actively visually search the environment in which they locomote. To avoid collision, a person must recognize objects sufficiently early to allow appropriate movement adjustments. Therefore, the therapist or coach who focuses training on only the movement-adjustment aspect of this task ignores the most critical component of object recognition.

the *perception-action coupling* involved in the long jump run-up. If *tau* is the visual variable that influences the long jumper's performance during this phase of the run-up, we would expect to see evidence of a coupling between the visually detected time-to-contact and movement corrections. This coupling would be best demonstrated by a linear relationship between the percentage of the total adjustment and the number of strides remaining to hit the take-off board. Montagne et al. (2000) presented evidence of this relationship in a study involving long jumpers of various levels of expertise. As you can see in figure 7.8, the percentage of the total amount of adjustment increased linearly for the final five strides from the take-off board. And, similar to what Lee, Lishman, and Thomson (1982) found for elite jumpers, approximately 40 percent of the total amount of adjustment occurred on the stride before the take-off board.

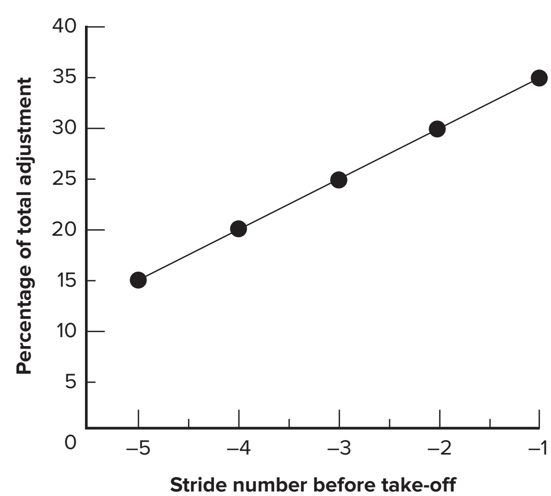

FIGURE 7.8 The percentage of the total amount of stride-length adjustments for the final five strides for the long jumpers in the experiment by Montagne et al. *Source:* Modified Figure 3 from Montagne et al. (2000). A perception-action coupling type of control in long jumping. *Journal of Motor Behavior, 32,* 37–43.

Researchers have found that other types of gait also involve adjustments during locomotion on the basis of visual time-to-contact information. Some examples are walking a given distance and stepping on the target with a specified foot (Laurent & Thomson, 1988); running and stepping on targets, as people do when crossing a creek on rocks (Warren, Young, & Lee, 1986); doing run-ups to the springboard and horse while performing the vault in women's gymnastics (Meeuwsen & Magill, 1987). In all of these activities, the persons adjust stride length on the basis of time-to-contact information as they near the targets.

A CLOSER LOOK

Vision Provides Body-Scaled Information When We Climb Stairs

Stair climbing is a common, everyday activity. But, how do we know that the stairs we need to climb are actually climbable? That is, how do we know that we can use a typical forward-stepping movement to climb a set of stairs? Vision operates in this situation in a way that is similar to how it enables us to determine if we can walk through a doorway without having to turn our shoulders to avoid contact with the sides of the doorway. The visual system detects and uses body-scaled information that involves the *relationship between the stair/step height and the person's leg length.* Researchers (e.g., Warren, 1984) have shown that if the riser height is equal to or less than 88 percent of the person's leg length, the person will judge that stair step to be climbable by a normal, forward-stepping movement. If the proportion exceeds 88 percent, the person will use a different movement pattern to climb the stair steps, such as children often do when they sit on the step first, or lift a knee to put the lower leg on the step first. In the language of *affordances* (chapter 5), stairs afford climbing with the typical pattern if the ratio of riser height to leg length is equal to or less than 0.88.

Avoiding contact with objects. When you walk through a doorway, you want to avoid contact with the sides of the doorway. How do you successfully achieve the action goal of this locomotor activity? Research evidence indicates that vision provides the motor system with *body-scaled information* about the size of a specific body part in relation to the size of the doorway. A person decides how to orient his or her body to walk through an open doorway on the basis of visually perceived information related to the proportion of his or her shoulder width to the width of the door opening. More specifically, Warren and Whang (1987) reported that a doorway needs to be 1.3 times wider than the person's shoulder width for the person to determine that he or she can walk through it without having to turn his or her shoulders.

A different type of object avoidance situation occurs when we need to go safely over an obstacle in our pathway. People can employ a variety of avoidance strategies while walking or running to accomplish this goal. Patla and his colleagues reported several studies in which they investigated the role vision plays in the strategy people select to go over an obstacle (e.g., Mohagheghi, Moraes, & Patla, 2004; Patla et al., 2002). Here again, vision provides predictive information that specifies to the motor control system the type of step-pattern alteration that will be needed to step over the object. The primary information is specified by the height, width, and shape of the object. In addition, predictions about how solid or fragile the object is are also important. For example, people will increase the height of their leading leg, which increases the amount of toe clearance, more for an obstacle perceived to be fragile than for an object perceived to be solid. And, in a study by Matthis, Yates, and Mayhoe (2018), walkers in a variety of outdoor natural terrains, from smooth to very rugged, demonstrated precise coordination between the biomechanics of their gait and eye movements that gathered the information the walkers needed to guide their foot placements. The walkers maintained a constant "look-ahead" gaze across all terrains.

SUMMARY

Much of our understanding of the control processes underlying the performance of motor skills comes from research evidence that has identified specific performance characteristics associated with a variety of types of skills. This discussion highlighted several of these characteristics.

- *Speed-accuracy skills,* which require a person to produce movement that is both fast and accurate, typically demonstrate a speed-accuracy trade-off.

That is, if the movement must be as accurate as possible, people move at a slower rate of speed than when accuracy is not important. Fitts' law provides a mathematical basis for predicting this trade-off on the basis of the task's movement distance and target size characteristics.

- ► Fitts' law applies to a wide range of motor skill performance situations in daily living activities and sports skills.
- ► Both open- and closed-loop motor control processes operate when a person performs a speed-accuracy skill.
- ► The role of vision in the control of speed-accuracy skills depends on the phase of the limb movement.

• Performance of *prehension skills,* which involve the reaching for and grasping of objects, demonstrates the synergistic temporal coupling of movement components that allow a person to achieve an action goal in a variety of situations. The transport and grasp components function interdependently by adjusting certain movement kinematics to adapt to specific characteristics of the object to be grasped and the manipulation goal of the prehensive action. Unlike manual aiming, pointing, and reaching, prehension movement kinematics vary during both the transport and the grasp phases as a function of what the performer intends to do with the object after it is grasped.

- ► The role of vision in the control of prehension skills is similar to that of speed-accuracy skills except that visual feedback influences the grasp component according to the grasp and object manipulation requirements of the intended use of the object.

• *Handwriting* demonstrates an important motor control characteristic known as motor equivalence, which means that a person can achieve the same action goal in a variety of situations that require movement adaptations dictated by the environmental context or by task characteristics such as size, force, direction, and muscles involved. The movement adaptations result in remarkable similarities in handwriting characteristics such as letter forms and the relative time relationship between strokes, among others.

- ► Vision influences the control of the overall spatial arrangement of words on a horizontal line and the production of accurate handwriting patterns.

• *Bimanual coordination skills* require the simultaneous performance of the two arms. Some tasks require symmetric bimanual coordination (i.e., both arms perform in the same way at the same time); others require asymmetric bimanual coordination (i.e., each arm performs differently). An important motor control characteristic of these skills is the natural, or intrinsic, spatial and temporal coupling of the arms, which means that we have a preference to move the arms symmetrically. Personal experience and research evidence shows that people can learn to uncouple the arms to perform asymmetric bimanual coordination skills. At the present time, researchers have not determined the specific motor control mechanism that underlies the control of arms in this uncoupled, asymmetric state, especially in terms of the roles played by proprioceptive and visual feedback.

• The *catching of moving objects* involves control processes similar to those for prehension actions except that catching involves intercepting a moving object and the grasping of the object ends the action. Catching involves three distinct movement phases: moving the arm and hand toward the oncoming object, shaping the hand to catch the object, and using the fingers and hand to grasp the object. The first two phases are typically completed by the time 75 percent of the object flight is complete.

- ► Vision plays an important part in the control of catching by providing advance information to the CNS to enable the spatial and temporal presetting of the arms, hands, and fingers before object arrival. Both central and peripheral vision operate in distinct ways to enable a person to catch an oncoming object.

  - ► Several factors related to vision influence the achievement of the action goal of catching a moving object. These include the amount of time of visual contact with the object, the portion of the object's flight during which visual contact occurs, and whether or not the hands can be seen during the object's flight.

- The involvement of vision in the control of striking a moving object relates to the influence of vision on the initiation of the striking movements and the compensatory adjustments to the initiated movements.
- The performance of locomotion actions, such as walking and running, is characterized by the rhythmic relationships that exist between step-cycle components, arm and leg movements, and the movement of the pelvis and thorax. Also, the maintenance of head stability is an important characteristic associated with locomotor activities. And a locomotion characteristic that has yet to be explained in terms of why it occurs is that spontaneous gait transitions (from walking to running, and running to walking) occur at certain gait speeds.
  - ► At the nervous system level, central pattern generators (CPGs) in the spinal cord provide the basis for the stereotypic locomotor movement patterns, although proprioceptive and visual feedback are also important for the control of locomotion.
  - ► The rhythmic structure of locomotion can be observed for the temporal relationships between the two legs as well as between the legs and arms.
  - ► The importance and role of vision in the control of locomotion are especially notable in locomotor activities that require the feet to contact an object after running a certain distance (e.g., long jumping in track and field) and during walking or running (e.g., ascending and descending stairs) and the avoidance of contact with objects (e.g., walking in a crowded hallway).

POINTS FOR THE PRACTITIONER

- When helping people initially learn speed-accuracy skills, you should emphasize achieving the accuracy goal more than the speed goal.
- The application of Fitts' law to practice or training contexts, especially in terms of the index of difficulty (ID), can provide a basis for creating easier and more difficult variations of a skill for people to practice.
- When helping people rehabilitate their prehension capabilities, provide functional prehension activities that include a wide range of object sizes, reach distances, grip configurations, and object uses.
- When helping people learn or rehabilitate their handwriting skill, emphasize that they need to look at what they are writing; monitor this aspect of handwriting performance for evaluation and correction purposes.
- When helping people learn or rehabilitate the performance of bimanual coordination skills, give special attention to the difficulty people may have with learning asymmetric bimanual coordination skills.
- When helping people learn or rehabilitate skills involving the interception of moving objects, such as catching and striking balls or other objects, emphasize the need to maintain visual contact with the object for as long as possible before it begins its flight and during its flight.
- When helping people learn or rehabilitate locomotor actions, monitor the rhythmic relationship between the arms and legs and include this aspect of gait performance for evaluation and correction purposes.
- When helping people learn or rehabilitate locomotor actions, emphasize the need to maintain head stability during locomotion; monitor head movement during locomotion to evaluate head stability in terms of vertical orientation and the amount of horizontal motion of the head.

- When helping people learn or rehabilitate locomotor actions, emphasize the need to maintain visual contact with an object that the person needs to step on or avoid contact with during locomotion; monitor this aspect of locomotion activity performance for evaluation and correction purposes.

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STUDY QUESTIONS

1. (a) Describe the speed-accuracy trade-off that occurs in the performance of many motor skills and give two motor skill performance examples. (b) How is Fitts' law related to the speed-accuracy trade-off phenomenon?
2. (a) Describe a prehension situation and indicate the components of this situation. (b) Describe the movement characteristics involved in each component, and how they might change in different prehension situations. (c) Discuss what is meant by the term *temporal coupling* and how it relates to prehension actions.
3. (a) Discuss how the skill of handwriting can provide a good example of the meaning of the term *motor equivalence.* (b) Discuss how your handwriting would be affected if you cannot see what you are writing.
4. Discuss why the performance of a skill requiring asymmetric bimanual coordination is difficult when it is first attempted.
5. Discuss how it is possible for a person to catch a ball without seeing his or her hands make the catch.
6. Discuss the role of vision in the skill of hitting a baseball or softball and the implications of this role for teaching a person this skill.
7. (a) What are two examples of the rhythmic structures involved in walking and running? (b) Describe how gait lends itself to the use of an identified order parameter and control parameter to be the basis for assessment of coordination problems.
8. Discuss why it is important to maintain head stability during locomotion.
9. (a) Describe a situation in which a person must contact an object, or objects, while running. (b) Discuss the influence of *tau* in this situation and how we know it influences the person's behavior as he or she performs this skill.

Specific Application Problem:
You are working in your chosen profession. Describe a skill (related to one of those discussed in this chapter) that you may help people learn or improve their performance of. How would you take into account the specific motor control characteristics associated with this skill as you develop strategies to help the people you are working with?